Proceedings of the Rainfall Simulator Workshop

Tucson, Arizona
March 7-9, 1979

U.S. Department of Agriculture
Science and Education Administration
Agricultural Reviews and Manuals • ARM-W-10/July 1979

Copies of this report are available on request from USDA-SEA-AR, Northern Plains Soil and Water Research Center, P.O. Box 1109, Sidney, Montana 59270.

Cover Photograph: Rainfall simulator used to study runoff and erosion at the Kansas Agricultural Experiment Station from 1931 to 1933.

Science and Education Administration, Agricultural Reviews and Manuals, Western Series, No. 10, July 1979

Published by Agricultural Research (Western Region), Science and Education Administration, U.S. Department of Agriculture, Oakland, Calif. 94612

Proceedings of the

Rainfall Simulator Workshop

Tucson, Arizona

March 7-9, 1979

C. R. Amerman
W. H. Blackburn
J. C. Brown
G. D. Bubenzer
R. M. Dixon
F. P. Eppert
G. R. Foster
G. F. Gifford
P. D. Green
W. R. Hamon
R. H. Hawkins
C. W. Johnson
R. S. Johnston
J. M. Laflen
L. J. Lane
D. K. McCool
K. C. McGregor
M. Martinez
L. D. Meyer
W. C. Moldenhauer
M. Molnau
C. K. Mutchler
E. L. Neff
J. B. Pate
K. G. Renard
A. R. Robinson
M. J. M. Romkens
R. E. Smith
E. Sundberg
N. P. Swanson
R. A. Young

U.S. Department of Agriculture
Science and Education Administration
Agricultural Reviews and Manuals • ARM-W-10/July 1979

PREFACE

Rainfall simulators, devices which apply water to research plots in a manner similar to natural rainfall, have been used in the United States for about fifty years in studies of runoff, erosion, and infiltration. In the early days, primary use of this tool was on cultivated farm land in the East and Midwest. However, during recent years an increasing use has developed on construction sites and rangeland throughout the United States. This has resulted in a proliferation of simulator designs, modifications, and operation techniques without a great deal of discourse between users.

In March 1979, the Science and Education Administration, U.S. Department of Agriculture, sponsored a Rainfall Simulator Workshop at Tucson, Arizona. This workshop was organized to discuss advantages and disadvantages of using rainfall simulators as tools in soil and water conservation research; to consider possible alternatives to rainfall simulation; to identify natural rainfall characteristics that need to be designed into rainfall simulators to achieve various objectives; and to provide specific suggestions to aid in the selection and use of simulators in runoff, erosion, and infiltration investigations. The SEA-AR organizing committee for this workshop was John M. Laflen, Ames, Iowa; L. Donald Meyer, Oxford, Mississippi; and Earl L. Neff, Sidney, Montana. These proceedings contain the complete texts of the titled papers and panel presentations at the workshop and brief summaries of rainfall simulator activities by each participant.

The committee thanks D. A. Farrell and A. R. Robinson, SEA, National Program Staff, Beltsville, Maryland, for their suggestions, encouragement, and support in organizing and conducting the workshop. However, credit for the success of the workshop lies with the participants. The committee sincerely appreciates the interest, the enthusiasm, and the participation in the discussions by those who attended.

Earl L. Neff, Chairman
Sidney, Montana
April 1979

AGENDA

RAINFALL SIMULATOR WORKSHOP

Tucson, Arizona

March 7-9, 1979

March 7 Chairman - E. L. Neff

0830-0920	Introductions and Comments - J. B. Pate, D. A. Farrell, A. R. Robinson, and K. G. Renard
0920-0940	Why Rainfall Simulation? - E. L. Neff
0940-1000	Discussion
1000-1015	BREAK
1015-1100	Geographical (Regional) Differences in Rainfall Characteristics Panel: C. K. Mutchler D. K. McCool
1100-1145	Discussion
1145-1300	Lunch
1300-1320	Rainfall Characteristics Important for Simulation - G. D. Bubenzer
1320-1340	Discussion
1340-1400	Methods for Attaining Desired Rainfall Characteristics - L. D. Meyer
1400-1420	Discussion
1420-1440	BREAK
1440-1500	Recent Developments in Simulator Design - G. R. Foster
1500-1520	Discussion
1520-1640	Description of Current Simulators and Simulator Activities. Participants (20 min. each) W. H. Blackburn, Texas A&M, College Station, Texas J. E. Box, SEA-AR, Watkinsville, Georgia J. C. Brown, U. of Nev., Reno, Nevada G. D. Bubenzer, U. of Wisc., Madison, Wisconsin

March 8 Chairman - J. M. Laflen

0800-1200	Continue Description of Current Simulators and Simulator Activities R. M. Dixon, SEA-AR, Tucson, Arizona R. E. Dohrenwend, Mich. Tech. Univ., L'Anse, Michigan G. R. Foster, SEA-AR, Lafayette, Indiana G. F. Gifford, Utah State Univ., Logan, Utah P. D. Green, BLM, Denver, Colorado W. R. Hamon, SEA-AR, Coshocton, Ohio BREAK C. W. Johnson, SEA-AR, Boise, Idaho R. J. Johnston, USFS, Logan, Utah

	L. J. Lane, SEA-AR, Tucson, Arizona
	G. C. Lusby, USGS, Denver, Colorado
	R. W. Lichty, USGS, Denver, Colorado
1200-1300	Lunch
1300-1700	Continue Description of Current Simulator and Simulator Activities
	D. K. McCool, SEA-AR, Pullman, Washington
	L. D. Meyer, SEA-AR, Oxford, Mississippi
	J. E. Morrison, SEA-AR, Temple, Texas
	C. K. Mutchler, SEA-AR, Oxford, Mississippi
	E. L. Neff, SEA-AR, Sidney, Montana
	BREAK
	M. J. M. Romkens, SEA-AR, Oxford, Mississippi
	R. E. Smith, SEA-AR, Fort Collins, Colorado
	N. P. Swanson, SEA-AR, Lincoln, Nebraska
	J. M. Laflen, SEA-AR, Ames, Iowa
	R. A. Young, SEA-AR, Morris, Minnesota

March 9 Chairman - L. D. Meyer

0815-1915	Rainfall Simulation as a Research Tool
	Panel: K. G. Renard
	R. H. Hawkins
	R. E. Smith
0915-1000	Discussion
1000-1015	BREAK
1015-1115	Interpretation of Rainfall Simulator Data
	Panel: M. J. M. Romkens
	J. M. Laflen
	R. A. Young
1115-1200	Discussion
1200-1300	Lunch
1300-1330	Need for Future Rainfall Simulator Comparisons
	J. M. Laflen - Leader
1330-1530	Open Discussion, Comments, Suggestions, etc.
	All Participants
1530-1600	Summary Comments
	D. A. Farrell
	A. R. Robinson
1600	Wrap-up - E. L. Neff

CONTENTS

COMMENTS--RAINFALL SIMULATOR WORKSHOP

By A. R. Robinson, USDA, SEA, NPS

Beltsville, Maryland 20705

Because of the need for data involving rainfall, this workshop was very timely. Data on rainfall runoff, erosion, sediment yield, and chemical yield variables are much in demand, particularly due to the current emphasis on nonpoint pollution, clean water, and a quality environment. Collecting adequate research data involving natural rainfall is very time consuming because natural weather is so variable. For example, there are instances where no runoff occurred from erosion plots after 3 years of operation and other instances at a different location where two 50-year-frequency rainfall events occurred within the same month. Through simulation, the hydrologic processes can be speeded up, and, in addition, the full range of rainfall amounts and hydrologic occurrences can be studied. The simulation must accurately duplicate rainfall intensity and energy and also soil conditions such as vegetative cover, tillage treatments, and antecedent moisture.

Several governmental programs have also created a demand for hydrologic information and data. Environmental impact studies of natural systems are being required to determine the optimum level of usage. Evaluations are required under the PL 92-500, Section 208, on nonpoint pollution control. The Rural Clean Water Program (RCWP) requires an evaluation (monitoring) of the effects of Best Management Practices on water pollution control. The Resource Conservation Act (RCA) requires an evaluation of past and present conservation practices and also a projection of future conservation needs for maintaining the soil and water resource base. The additional development of best management practices and systems requires research and development, much of which can be furthered using simulation techniques and computer modeling. Simulated rainfall systems can be used in the hydrologic and erosion studies required for reclamation and re-establishment of surface-mined areas and these methods can be used to obtain other types of data needed for modeling.

Rainfall simulators for studying infiltration, runoff, erosion, and sediment yield have proliferated. These systems use several devices for forming raindrops and for imposing the drops under energy levels and intensities simulating natural conditions. The size of simulators varies from small laboratory systems to those covering several acres. This workshop was designed to examine the many designs and conditions for rainfall simulators so that future studies can profit from past experiences and designs. For rainfall simulator data to be of wide use, some uniformity of equipment and test procedures is needed, and the data must be obtained under relatively standard conditions that closely simulate natural rainfall intensity and energy. Personnel from

several Federal and State agencies and Universities attended the Workshop, which presented an excellent forum on simulated rainfall experiences.

Mr. Earl Neff (USDA, SEA-AR, Sidney, Montana) and a committee planned the workshop, and Neff conducted the sessions. He is to be highly complimented for its success.

WHY RAINFALL SIMULATION?

Earl L. Neff, SEA research hydraulic engineer

Rainfall simulation, the technique of applying water to plots in a manner similar to natural rainfall, is a tool that has been used for many years in studies of erosion, infiltration, and runoff. All rainfall simulators for field use have certain common features. They are portable; have a supply source so that water is available when and where needed; have defined field plots that are treated or maintained according to the study objectives; have sprinkling mechanisms with which varying degrees of control can be exercised over water application rates and amounts; and there are devices and procedures for measuring the output from the plots. We will learn about several different simulators during this workshop, but most of the differences between the various designs will be in the design and operation of one or more of these common characteristics.

In the United States, simulation work began in the early 1930's, continued through the 1940's, and accelerated in the early- to mid-1950's. Following this surge, simulation experienced rather modest growth until about ten years ago. There has been increasing interest during the last decade as evidenced by the number of people who are building and using simulators of either new designs or modifications and improvements of existing designs. It is not my intent to give either a historical background of rainfall simulation or a review of rainfall simulators. For this, I refer you to the paper by Mutchler and Hermsmeier presented at the 1963 Winter Meeting and published in the 1965 Transactions of the American Society of Agricultural Engineers. The 1963 meeting was the last time that a group gathered to formally discuss this subject in some depth. Many of those who participated in the program in 1963 are with us here in Tucson. L. D. Meyer, C. K. Mutchler, N. P. Swanson, and G. D. Bubenzer will provide continuity between the two programs and will help bring us up to date on the advances made during the intervening fifteen years.

The objectives in organizing this workshop were to discuss various aspects of rainfall simulation including:

1. Why should rainfall simulation be used as a tool;
2. What rainfall characteristics need to be considered when using simulators;

USDA, Science and Education Administration, AR, Northern Plains Soil and Water Research Center, Sidney, Montana 59270

3. How can these characteristics be simulated and;
4. How can simulator data best be collected, analyzed, interpreted, and extrapolated to satisfy specific research needs?

I have elected to address the first of these questions, but in doing so I will touch briefly on the others.

One thing I found when discussing rainfall simulation is that there are very few fence straddlers. Most people who have had experience are either enthusiastically for or strongly opposed to simulation. One scientist, responding to an early inquiry regarding the value of holding this workshop, started a 2-page memo with a statement to the effect that spending any more money on rainfall simulators would be the biggest waste of money in research that he could think of at the moment. While you may not agree with his thesis, you certainly have no problem understanding it. On the other hand, there are many scientists, and not just those at this workshop, who have used rainfall simulation to make very significant contributions to our knowledge of runoff, erosion, and infiltration.

About two years ago, when I became interested in simulation, I read some of the literature and discussed the subject with a few people who had experience. I found that rainfall simulation has a number of disadvantages. Among them are:

1. Rainfall simulators are expensive to construct and use because of the cost of components and assembly and the number of people required to operate them.

2. The areas treated are small, ranging from a fraction of a square meter up to several hundred square meters, depending on the simulator design. These small areas may or may not be representative of the general area of concern. For example, things such as rodent holes, large bushes and plants, etc. on the plots can have a disproportionate effect on the results.

3. Simulators do not produce drop-size distributions that are representative of natural rainfall. Simulators with tube-type drop formers produce drops within a narrow range of sizes, and drop size can be adjusted only by changing the size of the tubes. Simulators with nozzle-type drop formers produce drops over a wide range of sizes, but they are smaller than some natural thunderstorm-type raindrops.

4. Simulators do not produce rainfall intensities with the temporal variations representative of natural rainfall. Some simulators can produce different intensities, but they are usually varied between runs and not within runs.

5. Some simulators do not produce drops that approach the terminal velocity of corresponding size drops of natural rainfall. The lower velocities in combination with smaller drop-size distributions result in lower kinetic energy than that produced by natural rainfall. Kinetic energy of simulators with nozzle-type

drop formers and free-falling drops may be only 40-50% of natural rain. There are, however, simulators designed with nozzles pointed down and the drops applied under pressure which do approach the energy of natural rain.

If a person applied himself, I'm sure he could come up with additional objections to rainfall simulators, but I think I have listed the most serious. After considering this rather imposing and discouraging list of problems, it is logical to wonder why anyone would want to even think about using one of these devices. Well, on the other side of the coin, there are also certain advantages. Among them are:

1. Rainfall simulators are cost-efficient. Because of the degree of control that can be exercised over simulator operation, the cost per unit of data collected is quite low when compared to unit costs of long term experiments depending on natural rainfall. Long term experiments require not only the cost of initial instrumentation but also a great deal of personnel time for plot and instrument maintenance, and servicing during periods in which little or no data are being collected. We all realize that people are probably the most expensive thing we pay for in an experiment.

2. Rainfall simulators provide a maximum of control over when and where data are to be collected; plot conditions at test time; and, within design limitations, rates and amounts of rain to be applied. If an investigator must depend on natural rainfall it may take many years to collect data with the required combinations of rainfall amounts and intensities, land management sequences, and crop growth stages for valid analysis and interpretation. The degree of control afforded by rainfall simulators provides a technique for collecting a great deal of data in a relatively short time.

While my list of disadvantages is longer than the list of advantages, they really boil down to matters of control and efficiency. If these are accepted, the question that arises is whether or not the advantages are important enough to accept the trade-offs imposed by the limitations. This is the basic question that this workshop was organized to address and all of these things will be discussed in more detail in the next three days.

With the understanding that I am free to change my mind between now and Friday afternoon, I would like to make a few observations.

1. Rainfall simulators have some serious limitations that we must recognize and respect when designing experiments and analyzing and interpreting results. This statement really should go without saying, but I think that many times we accept data without considering the possibility of instrument error or questioning how well the data represent the real world. It is important to recognize sources of potential error as we attempt to increase the accuracy and precision of our research results and interpretation.

2. Simulators should not be considered the panacea for all our problems in runoff, erosion, and infiltration investigations.

3. There needs to be a continuing effort to modify existing or design new simulators to overcome some of the limitations.

4. The most important observation is that rainfall simulators are viable tools if they are used with knowledge, with understanding, and with a certain amount of caution. I really see no alternative to rainfall simulation in many cases because the scientific environment of today demands rapid answers. We can no longer enjoy the luxury of setting up long term experiments that may require 10 to 20 years before conclusive results are obtained. In 10 or 20 years, different people will be asking different questions that probably cannot be answered by experiments designed today. I am not implying that we should close out all of our long term watershed projects for them. I am, however, suggesting that watershed and simulator studies can compliment each other to accomplish several things.

   A. Watershed data can be used to verify simulator results and to develop methods for expanding results from plot size to watershed size areas.

   B. If this is successful, simulators may be used to expand the results of watershed studies over a wider size range of rainfall events than may have been experienced during the project record.

   C. Simulators may be used to extrapolate watershed results to other areas and this is where maximum benefits can be realized from simulator use.

It is a foregone conclusion that rainfall simulation is not only going to continue but it is going to increase. There are too many people now using simulators or planning to use them in the future to think otherwise. Now the questions we must face are:

1. How much confidence can we place in simulator results? We know that they are not perfect, but how good are they?

2. How do results from simulators of different designs compare? There are several different simulators that have been designed and built but there is little information available on how they compare. This question needs to be answered so that the best design can be selected to meet specific study objectives.

3. How many different kinds of simulators do we need? Are geographic, climatic, and research objective differences important enough that we need many different designs or is it possible to standardize a few so that people in different parts of the country working on similar studies are using the

same simulator and collecting data in the same way? We all know that there cannot be one simulator that will do everything under all conditions, but I not only think we can, I think that we must standardize as much as possible in order to obtain maximum benefits from our shrinking research resources.

It is obvious that these questions cannot be answered in a three-day workshop. However, we can discuss them, decide which of them may need immediate attention, and start planning ways to find the answers.

The title of my presentation is "Why Rainfall Simulation?". My answer to this question is that there is no other tool available that will quickly and efficiently provide the necessary data when and where it is needed. We have no alternative.

GEOGRAPHICAL DIFFERENCES IN RAINFALL

C. K. Mutchler and K. C. McGregor
research hydraulic engineer and agricultural engineer[1/]

INTRODUCTION

Before talking about geographical differences in rainfall, we must define how rainfalls are different. Also pertinent are the relationships of rainfall characteristics with each other. Because rainfall characteristics are complex, we need to consider some parameters that lessen the number of variables that must be dealt with.

After the parameters are described, we discuss how they may vary from region to region. And finally, we present some alternatives for using rainfall parameters in simulating rainfall for research.

Rainfall Characteristics

By definition, rainfall is made up of water drops of various sizes and shapes falling in an atmosphere of various temperatures, humidity, and wind. Very little data is available on individual drop behavior in a rainstorm. Most studies of raindrop behavior have been made using waterdrops in an enclosed atmosphere.

Wind--Wind movement and velocities have a profound effect on all aspects of rainfall. In fact, wind or air movement is necessary for rainfall to occur. For example, the two basic essentials of thunderstorm rainfall are a supply of warm, unstable air and some type of lifting action (1). Also, wind affects the raindrop fall vector and velocity near impact with the soil.

Wind speed and direction data are readily available, but we haven't found any studies of coordinated wind and rainstorm data.

Drop shape--Studies in Illinois (2) with a raindrop camera have shown various shape changes indicating that raindrops may vibrate so that the long axis of the non-spherical drop shape may occur in any direction. This shape change is probably due to wind velocity or turbulence. Gunn and Kinzer (3) also reported that freely falling water droplets have been observed to vibrate strongly and spin, thus producing definite departures from spherical symmetry.

1/ Sedimentation Laboratory, Science and Education Administration, U.S. Department of Agriculture, Oxford, MS 38655.

In an enclosed atmosphere, waterdrops formed from some type of drop former begin their descent with a tear drop shape because of the detachment process. After a brief period of vibration, surface tension that causes the waterdrop to tend to be spherical and air resistance pushes the drop into the typical shape at terminal velocity, one resembling a bread bun, spherical on top and flattened on the bottom (4) for sizes greater than about 3 mm. Those drops smaller than 3 mm are approximately spherical at terminal velocity.

We found no studies of raindrop shape at impact in the open atmosphere. Most data on drop size have been collected as some calibrated measure of drop mass.

Terminal velocity--Studies of raindrop erosion generally have assumed that raindrops were falling at terminal velocity before impact. This may have some merit because wind velocities nearest the ground level are generally the lowest in the surface air mass. But, it is questionable if this reduction in wind velocity would make an appreciable change in the raindrop fall vector.

Terminal velocities of waterdrops based on measurements by Laws (5) and by Gunn and Kinzer (3) have been particularly well accepted. Laws reported velocities for drops with diameters from 1.2 to 6.1 mm. Drop sizes studied by Gunn and Kinzer ranged from about 0.08 to 5.8 mm.

Dropsize distribution--The drop sizes within a given volume of the atmosphere are generally distributed from many very small drops to a few of the largest drops (6). Only in one instance has rainfall of uniform drop sizes been reported. Bentley (7) observed such rainfall and supposed that it was due to raindrop formation from the melting of snow crystals or granular snow particles that are often of a uniform size.

Several researchers have reported work on raindrop size distributions as related to rainfall intensities (6) (8) (9) (10). However, little is available to show the effect of location or storm type. Several references by meteorologists described distributions in the air mass made with radar observations; these may not accurately reflect the distributions immediately before impact with the ground.

Hudson (9) presented smoothed curves that appear to be normal for intensities up to 4.5 iph, based on percent of rain volume at the different drop sizes. For higher intensities, the drop size distribution seems to approach a log normal shape (our interpretation). Laws and Parsons (10) showed curves of drop size-volume distribution that also appear to be normal for intensities up to 4 iph which was the highest intensity curve they gave. Laws and Parsons stated that the size distribution of any rainfall rate is only approximately known. They reported that the precision of their size distributions in tabular form is much less than the values imply. In addition, the tabular values for rainfall rates of 0.01, 4.0 and 6.0 inches per hour, and for rain drops smaller than 0.5 mm were derived by extrapolation. They further stated that considerable doubt exists as to the variability of size-distribution from time to time. However, their research has been well accepted and

much use has been made of their tabulated size distributions for intensities of .01, .05, 0.1, 0.5, 1, 2, 4, and 6 iph.

Simple Relationships

The term simple is used only to differentiate from those relationships of rainfall that have been parameterized and will be discussed later. Truly, little about rainfall is simple.

Terminal velocity--Such measurements have been made in still air. In this case, terminal velocity (TV) is a square root function of drop diameter (D) for diameters smaller than 3 mm (25). Because the drops become more flattened with larger drop diameter, the relationship TV = f(D) is not well formulated. Most of the relationships are given in graphical form (3) (5).

The impact velocities of raindrops are of course the major interest. Unfortunately, these velocities are extremely difficult to measure with any confidence. Also, wind effects enter in to make the problem more difficult.

Intensity--Rainfall intensity depends on storm-type, location and probably on several other variables. Thunderstorms generally have high intensities whereas stagnate cold front storms have lower intensities. Other type storms, the orographic and combination of the aforementioned types, have intensities depending on the particular combinations (11).

In general, the evidence seems to support the notion that drop sizes are larger where there is greater vertical movement within the raincloud. In mature thunderstorms there is much turbulence and active vertical motion. There are violent updrafts and downdrafts side by side. Thunderstorms are often classified as either air mass or frontal (1) (12). Air mass thunderstorms result from vertical displacement of air within a single air mass. An example of how such displacement can be caused is the heating of air at the ground surface by thermal convection. Another is the movement of a single air mass against a mountain. Frontal thunderstorms result when there is an advancement of a warm air mass against cold air or of a cold air mass against warm air. In either case, warm moist air is caused to rise. In addition, heavy showers and thunderstorms advance ahead of cold fronts when there is a pre-cold-frontal squall line. Squall lines are difficult to predict. There are different theories about what causes them. In any event, vertical movement of air is a characteristic of all thunderstorms. It can be seen there are many types of storms in reference to depth and vertical velocities which can affect storm intensities.

The intensity distribution within a rainstorm was studied by Wischmeier (13) as advanced, intermediate, and delayed intensity storms. Dividing storms into these different intensity patterns did not help him to explain any of the variability between EI (discussed later) and soil losses from fallow erosion plots. The storm intensity distribution has been generalized by SCS (14) as Type I storms and Type II storms. These

are long-term average representations and would probably not apply to a given single storm.

Orographic storm types are restricted to hilly or mountainous areas. However, the other storm types may occur at most locations with one or more types being dominant. The point is that storm type affects intensity and occurs in various combinations for different locations with some notable exceptions.

Mean intensities for given storm durations are well documented over the U. S. However, we didn't find any documentation of instantaneous intensities as related to other parameters. Perhaps the data closest to defining instantaneous rates on an area basis are maps of the U.S. showing maximum precipitation for given durations.

Storm amounts--These data are well documented in Weather Bureau publications along with intensity-duration-frequency curves. Assuming familiarity with these publications, no more will be said about this topic although it is the major data source for regional rainfall studies.

Parameter Relationships

The major parameter to date used to relate rainfall to erosion is the EI relationship where the annual EI, called the R-factor in the Universal Soil Loss Equation (USLE), is directly proportional to erosion (15). Other parameters such as momentum, velocity times diameter, intensity, and various combinations of the same were studied (16). All were based on knowledge of drop size distribution as a function of rainfall intensity, and impact velocity estimated from terminal velocities of waterdrops falling in still air.

Impact velocity--Raindrop impact velocities are estimated to be equal to the terminal velocities of water drops. This estimate neglects any wind effects and any effect of non-normal impact on sloping ground. Also, practical considerations require use of a single velocity value for some range in drop size. Thus, velocity data are usually gotten from a function of diameter given in a graphical form (see Fig. 2 of ref. 15).

Drop size distribution--Rainfall drop size distributions have been parameterized with the D_{50} drop size where 50 percent of the total volume is less than D_{50} and 50 percent is larger. Relationships have been derived for D_{50} as a function of rainfall intensity. Changes in D_{50} values for different intensities are indications of changes in drop size distributions. Unfortunately, the intensity-drop size distribution relationship is not well defined because the same phenomena that cause different intensities also produce somewhat different drop sizes for the same intensity (17).

Computations of rainfall energy should not be based on the D_{50} parameter alone. Tabular drop-size distribution data for different intensities can be used. Use can also be made of the D_{50} and other percentile curves giving average diameters of rain drops that contribute

to the respective percent of rainfall volume at a particular intensity. Smith and Wischmeier (18) reported that energy values computed from Laws and Parsons' median drop size data alone are from 10 to 15 percent high. However, the D_{50} parameter can be used to give general estimates of energy values. This parameter also provides a simple and quick way to compare the result of different researchers.

Various formulas have been presented for D = f(I). Laws and Parsons (10) gave, for median drop sizes in mm and intensities in inches per hour,

$$D_{50} = 2.23\ I^{0.182}$$

Other researchers obtaining different results include Hudson (9), Mihara (19), Carter et al. (8), and McGregor and Mutchler (17). The curves of Hudson and of McGregor et al. both included drops at higher intensities and showed that median drop size decreased for intensities above 4 and 2 inches per hour, respectively; whereas Laws, et al. predicted that D_{50} increased for all drop sizes. Wischmeier recognized the apparent error in Laws and Parsons' equation and prescribed use of it for D_{50} to 3 inches per hour and the 3 inch value for intensities greater than 3 inches per hour (20). Naturally, the writers recommend their own equation

$$D_{50} = 2.76 + 11.40 \exp(-1.04\ I) - 13.16 \exp(-1.17\ I)$$

which is continuous and used for all intensities greater than zero.

Energy--Kinetic energy computations depend on mass and velocity. It was shown above that both mass and velocity are functions of rainfall intensity. Thus a rainfall recorder chart can be used to numerically compute the KE of any rainfall. Wischmeier (15) derived a relationship of KE and I

$$KE = 916 + 331 \log_{10} I$$

where KE is in foot tons per acre inch and I is intensity in inches per hour. This equation was derived to use the midpoint values of intensity increments. The total KE for each increment is obtained by multiplying the computed KE by the amount of rainfall (inches) in the interval.

EI index--This parameter was devised and selected by Wischmeier et al. (15) as the best predictor of erosion from a given storm. The parameter is composed of the storm's total KE (computed as described above) divided by 100 and multiplied by the maximum 30-min intensity of the storm. For periodic computation, rainfalls of less than 0.5 inch and separated from other rain periods by more than 6 hours are neglected unless as much as 0.25 inches of rain falls in 15 minutes (20). Also, I is limited to values less than or equal to 3 iph for computation of EI and to 2.5 iph for I_{30} (20).

Regional Rainfall Distribution

As seen from the above discussion, the major characteristics of

rainfall are liable to vary with location and at a given location. Those characteristics routinely measured by the National Weather Service are, of course, readily available. However, those that intimately describe a rainfall are much less available and much more difficult to measure. The best example we know of representing regional differences in rainfall is the derivation of the R-factor by Wischmeier for use in the USLE (21).

Current values of the erosion index are given in Agr. Handbook 537 published in 1979 (20). Two types of distributions of EI are given. One involves distribution of EI throughout the year at a given location and the other involves location differences of average annual EI. Only recently have the EI values been extended to the western U.S. (another author will discuss this development). Thus, the EI distributions give one method of considering regional rainfall differences.

Wischmeier (20 (22) reported work the Agricultural Research Service did to establish a relationship between annual EI values and rainfall intensity-duration frequencies published by the U.S. Weather Bureau. They derived the equation

$$EI = 27.38\ P^{2.17}$$

where P is the 2 year, 6 hour rainfall in inches. This relationship was evaluated for the Western Plains and North Central States. Later research by Engineering Service, Inc. reported by Ateshian (23) showed a rational basis for the EI index with the 2 yr, 6 hr. rainfall. For the extreme western part of the U.S. delineated by the SCS Type I rainfall

$$R = 16.55\ (P_6)^{2.2}$$

For the remainder of the U.S. (SCS Type II rainfall area)

$$R = 27.00\ (P_6)^{2.2}$$

where P_6 is the 2 year, 6 hour rainfall amount.

With these relationships, EI becomes an attractive parameter to use in considering regional rainfall differences as they affect soil erosion. Wischmeier extended the EI representation to Hawaii in Agr. Handbook 537 (20).

The authors have tried to keep in mind that this paper is intended for a workshop on simulated rainfall for erosion research, hence the attention to raindrop characteristics. Unfortunately, the evidence indicates that drop sizes in rainfall vary for storm type, for location, and within stormtypes. Thus, the problem of closely simulating specific storms may be quite difficult.

Kinnell (24) reported a study of the erosiveness of rainfall based on data from Florida, New Jersey, and the Marshall Islands. He calculated values of three parameters--momentum, kinetic energy, and KE per unit horizontal area of the drop. He concluded that these parameters vary both for rain type and location. He also concluded that considerable variation

in the relative drop-size distribution occurs with any one rain type. No evaluation of the relative erosive value of the 3 parameters was made.

In view of the variable nature of rainfall, the authors offer the following alternatives.

1. Simulate drop size distribution and intensity-duration characteristics of specific rain types.

2. Simulate rainfall characteristics as represented by periodic sampling for a year or greater as exemplified by data of Laws and Parsons, Carter, and McGregor-Mutchler.

3. Calibrate the simulator with either a simulator of known performance or against natural rain using an erosion plot.

Alternative 1 offers the possibility of being more precise. However, the variation of drop size distributions within the rain types would be a problem especially because little or no basic data is available.

Alternative 2 obviously is better suited to average annual erosion efforts. Data is available and past analytical results are available. Use of this alternative is also reinforced by the conclusion that the U.S. can be regionalized where different rain types occur in relatively equal proportions over the regions. This alternative is supported by the EI distribution for location and for annual variation, delineation of the U.S. by SCS Type I and II rainfall, and the relationship of EI and the 2 year, 6 hour rainfall. The alternative has built in error when used for simulation of single storms which is an obvious disadvantage.

Alternative 3 has the advantage of evaluating rainfall by its effect on the variable of major interest, erosion. Use of it requires knowledge of and concern of rainfall variation between location and storm type. This essentially is the method used to determine K-factor values of soil using erosion plots. It has the disadvantages of being inefficient of time and there is a question whether data gathered with this method can be extrapolated to other locations, soils, and slopes.

We think that any of the alternatives can be used successfully with due consideration of differences in rainfall characteristics. However, the question must be asked: Is it worth it? With this as a major consideration, we think alternative 1 too difficult in light of the high variability of the other elements of the soil erosion system. The second alternative seems best by far, and the third alternative useful when the second cannot be used.

LITERATURE CITED

(1) Shaw, R. H. and C. R. Elford.
1958. Iowa weather patterns. Iowa Farm Science, 13(2):11-14.

(2) Jones, D. M. A.
1959. The shape of raindrops. Illinois State Water Survey Circ. 77.

(3) Gunn, R., and G. D. Kinzer.
1949. Terminal velocity of water droplets in stagnant air. J. Meteorology, 6:243-248.

(4) Mutchler, C. K.
1967. Parameters for describing raindrop splash. Jour. of Soil and Water Consv., 22(3):91-94.

(5) Laws, J. Otis.
1941. Measurements of the fall-velocity of water drops and rain drops. Trans. Am. Geophys. Union, 22:709-721.

(6) Best, A. C.
1950. The size distribution of rainfall. Quart. J. Royal Meteorol. Soc., 76:16-36.

(7) Bentley, W. A.
1904. Studies of raindrops and raindrop phenomena. Monthly Weather Rev., 32:450-456.

(8) Carter, C. E., J. D. Greer, H. J. Brand, and J. M. Floyd.
1974. Raindrop characteristics in south central United States. Trans. of ASAE, 17:1033-1037.

(9) Hudson, N. W.
1963. Raindrop size distribution in high intensity storms. Rhodesian Jour. Agr. Res, 1:6-11.

(10) Laws, J. O. and D. A. Parsons.
1943. The relation of raindrop size to intensity. Trans. Am. Geophys. Union, 24:452-460.

(11) U. S. Department of Agriculture.
1941. Climate and man. Yearbook of Agriculture.

(12) Blair, T. A. and R. C. Fite.
1965. Weather Elements. Fifth edition, Prentice-Hall, Inc., Englewood Cliffs, N.J., pp. 178-181, 195-199.

(13) Wischmeier, W. H.
1959. A rainfall erosion index for a universal soil loss equation. Proc. Soil Sci. Soc. Amer., 23:246-249.

(14) U. S. Department of Agriculture.
1968 (revised Apr., 1973). A method for estimating volumes and rate of runoff in small watersheds, SCS-TP-149. Soil Conservation Service, Jan.

(15) Wischmeier, W. H. and D. D. Smith.
1958. Rainfall energy and its relationship to soil loss. Trans. AGU, 39:285-291.

(16) Wischmeier, W. H.
1972. Upslope erosion analysis from Environmental impact on rivers. H. W. Shen Publisher, CSU, Fort Collins, CO.

(17) McGregor, K. C. and C. K. Mutchler.
1976, 1977. Status of the R-factor in northern Mississippi in soil erosion: prediction and control. Proceedings of National Soil Erosion Conference at Purdue University, May 24-26, SCSA, Ankeny, Iowa, pp. 135-142.

(18) Smith, D. D. and W. H. Wischmeier.
1962. Rainfall erosion. Advances in Agronomy, 14:109-148.

(19) Mihara, Y.
1952. Raindrops and erosion. Natl. Inst. Agri. Sci., Tokyo, Japan.

(20) Wischmeier, W. H. and D. D. Smith.
1979. Predicting rainfall erosion losses--a guide to conservation planning. Agr. Handbook No. 537, USDA.

(21) Wischmeier, W. H.
1962. Rainfall erosion potential. Jour. Agric. Eng., 43:212-225.

(22) Wischmeier, W. H.
1974. New developments in estimating water erosion. Proc. 29th Ann. Meeting of SCSA, pp. 179-186.

(23) Ateshian, J. K. H.
1974. Estimation of rainfall erosion index. Jour. Irr. and Drain Div., Proc. ASCE, 100:293-307.

(24) Kinnell, P. I. A.
1973. The problem of assessing the erosive power of rainfall from meteorological observations. Soil Sci. Soc. Amer. 37: 617-621.

(25) Spilhaus, A. F.
1948. Drop size, intensity, and radar echo of rain. Jour. of Meteorology, 5:161-164.

REGIONAL DIFFERENCES IN RAINFALL CHARACTERISTICS AND THEIR INFLUENCE ON RAINFALL SIMULATOR DESIGN

D. K. McCool, SEA-AR agricultural engineer[1/]

INTRODUCTION

Rainfall characteristics such as intensity, drop-size distribution, energy, and duration relationships vary widely across the United States. Any rainfall simulator developed to simulate natural infiltration or erosion conditions in a region should be capable of approximating the natural rainfall characteristics if realistic results are to be obtained. The purpose of this paper is to briefly examine some of these rainfall characteristics, their variation across the United States, and their influence on simulator design.

INTENSITY

The Southeast, influenced by tropical air masses, exhibits much higher intensities for a given duration and return interval than does the Pacific Northwest, which is influenced by maritime air masses (Figure 1) (2). Areas east of the Rocky Mountains, influenced by continental and tropical air masses and the meeting of the two, generally exhibit characteristics between these extremes; however, in certain areas convective storms can release large quantities of water over small areas in a very short period of time. The mountainous areas of the West exhibit large local variation because of orographic influences. A rainfall simulator should approximate the intensity characteristics of the storms of concern in a region.

DROP-SIZE CHARACTERISTICS

Studies of raindrop size characteristics have been conducted at various locations in the United States and throughout the world. Perhaps the most widely used study in the United States is that of Laws and Parsons (4), who studied drop-size distributions in Washington, D.C. The data from that study have been used in design of many of the current rainfall simulators and sprinkling infiltrometers (6, 9, 11). The data also have provided information for energy vs. intensity relationships for use in the development of the energy-intensity factor in the Universal Soil Loss Equation (12). Hudson (3) and

1/Land Management and Water Conservation Research, USDA-SEA-AR, Washington State University, Pullman, Wash. 99164. In cooperation with the College of Agriculture Research Center, Washington State University.

Carter et al. (1) showed somewhat different relationships, particularly for intensities greater than four inches per hour (Figure 2) (1). Results of a study at Pullman, Washington, and Corvallis, Oregon (5), showed a drop size vs. intensity relationship quite similar to that developed by Laws and Parsons, although the intensities were much smaller than most of the Laws and Parsons data. The kinetic energy vs. intensity relationship was different for the two sets of data; the Laws and Parsons drop-size distributions exhibit positive skew, whereas the Pacific Northwest data exhibit neutral skew and hence lower kinetic energy at a given intensity.

Approximating natural drop-size and kinetic energy (terminal velocity) characteristics while retaining desirable intensity has been one of the most vexing problems in rainfall simulator design. Currently available simulator nozzles approximate natural drop size and kinetic energy only at intensities higher than naturally occurring rain. In order to meet these criteria, most designers of simulators have been forced to use intermittent rainfall application. For some simulator uses, this is not a satisfactory solution.

DURATION AND INTENSITY RELATIONSHIPS

Rainfall intensity can vary considerably during storm periods. Typical storm patterns Type I, IA, II, and IIA have been developed (Figure 3) (7). These storm distributions are closely associated with climatic regions (Figures 1 and 4) (10, 2, 8), although a given distribution can occur in nearly any region. Storm patterns can vary between seasons; i.e., storm pattern Type II is fairly typical for summer storms in the Palouse Region of the Pacific Northwest, yet winter storms, when most of the erosion problems occur, are more typically Type IA distribution--long duration and low intensity. In this case, the duration vs. intensity relationship at the season of concern should govern the simulator design.

SUMMARY

Rainfall simulator design is usually a compromise. It is not possible to reproduce all rainfall characteristics in simulator design. Yet regional differences are significant and must be considered.

REFERENCES CITED

(1) Carter, C. E., J. D. Greer, H. J. Braud, and J. M. Floyd.
1974. Rain-drop characteristics in south central United States. Trans. ASAE 17:1033-1037.

(2) Hershfield, D. M.
1961. Rainfall frequency atlas of the United States, for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. U.S. Weather Bureau Tech. Report 40.

(3) Hudson, N. W.
1963. Raindrop size distribution in high intensity storms. Rhodesian J. Agr. Res. 1:6-11.

(4) Laws, J. O. and D. A. Parsons.
1943. The relation of raindrop size to intensity. Trans. AGU 24:452-460.

(5) McCool, D. K., M. J. Robinette, J. T. King, M. Molnau, and J. L. Young.
1978. Raindrop characteristics in the Pacific Northwest. 1978 Fall Meeting of the AGU, San Francisco, Calif., Abstract.

(6) Meyer, L. D. and D. L. McCune
1958. Rainfall simulator for runoff plots. Agr. Engr. 10:644-648.

(7) Soil Conservation Service, U.S. Department of Agriculture.
1970. Estimating peak discharges for watershed evaluation storms and preliminary designs. TSC Tech. Note - Hydrology - PO - 2. West Regional Technical Service Center, Portland, Oregon.

(8) Soil Conservation Service, U.S. Department of Agriculture.
1971. Engineering Field Manual Notice 4, Chapter 2, Estimating runoff. Central Technical Unit, Hyattsville, Maryland.

(9) Swanson, N. P.
1965. Rotating-boom rainfall simulator. Trans. ASAE 8:71-72.

(10) U.S. Environmental Protection Agency.
1973. Comparative costs of erosion and sediment control, construction activities. EPA-430/9 - 73 - 016.

(11) Wilm, H. G.
1943. The application and measurement of artificial rainfall on types FA and F infiltrometers. Trans. AGU 24:480-487.

(12) Wischmeier, W. H. and D. D. Smith.
1958. Rainfall energy and its relationship to soil loss. Trans. AGU 39:285-291.

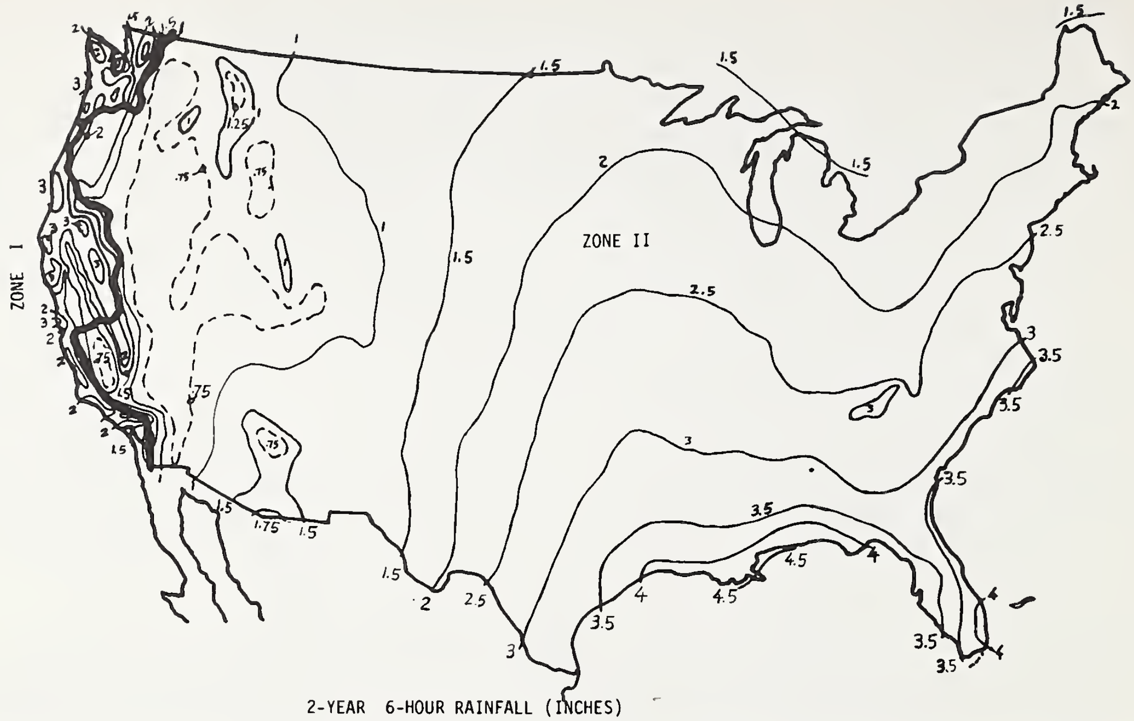


Figure 1--Depths of the 2-yr, 6-hr rainfall, inches, and storm distribution regions in the United States (2, 10).

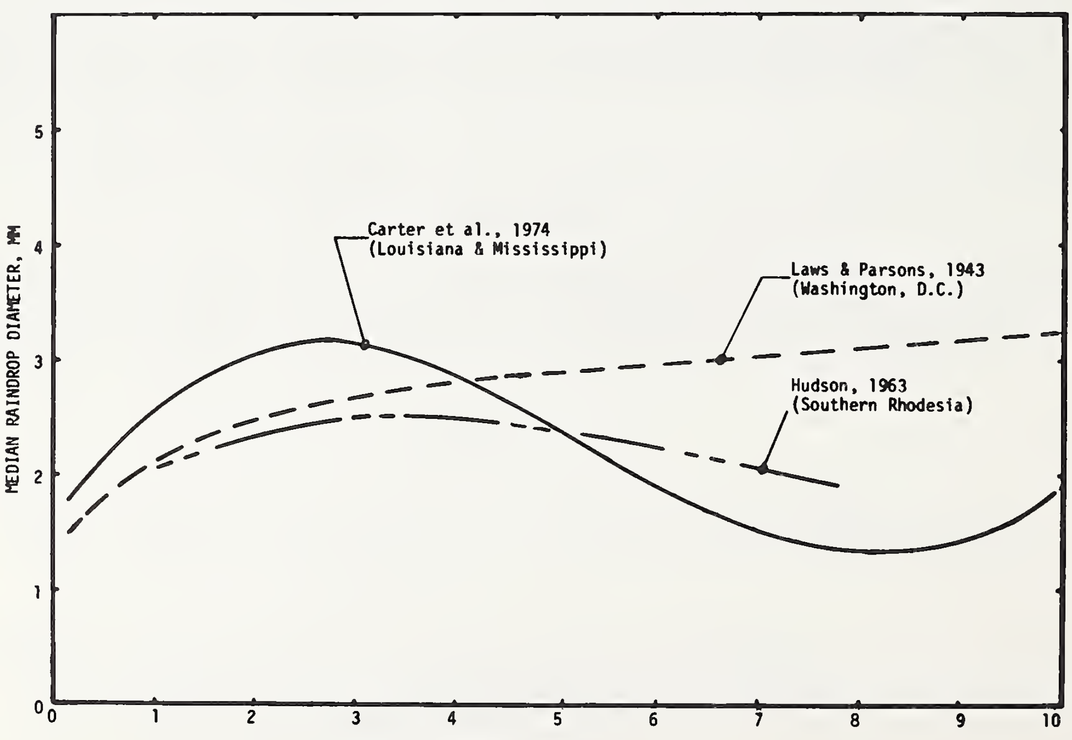
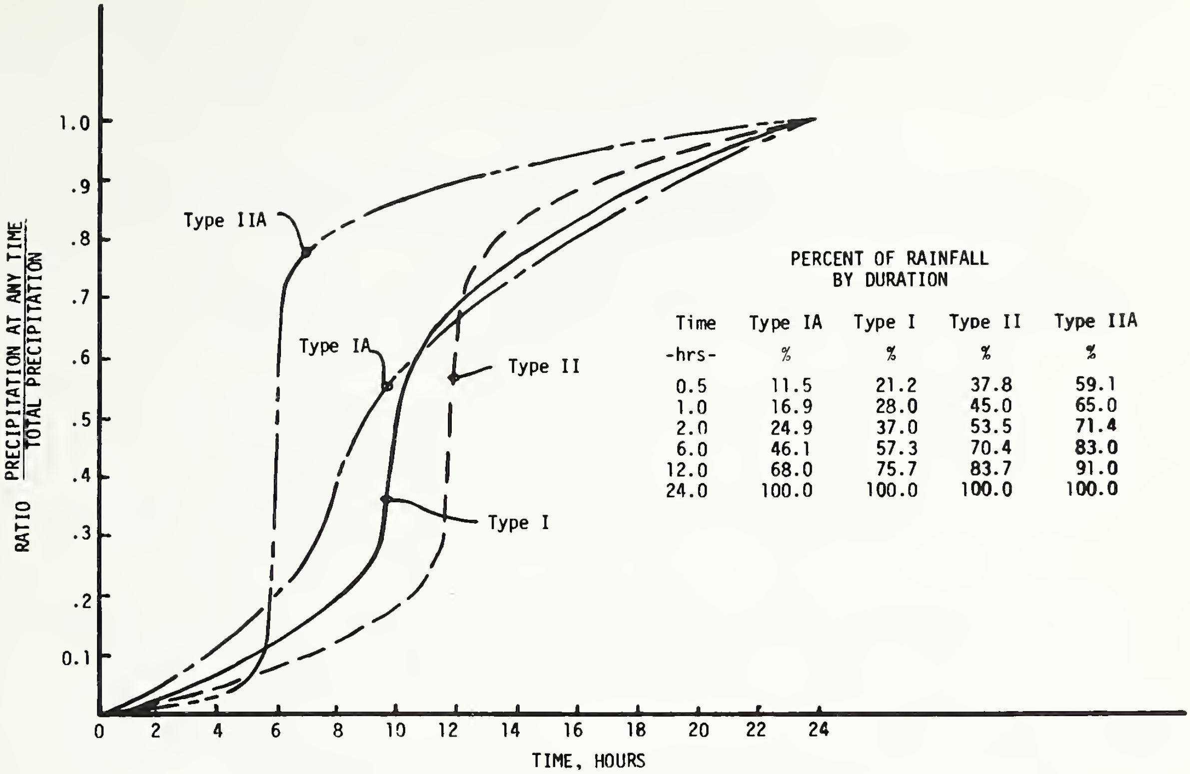


Figure 2.--Raindrop size and intensity relationship (1).



Time	Type IA	Type I	Type II	Type IIA
-hrs-	%	%	%	%
0.5	11.5	21.2	37.8	59.1
1.0	16.9	28.0	45.0	65.0
2.0	24.9	37.0	53.5	71.4
6.0	46.1	57.3	70.4	83.0
12.0	68.0	75.7	83.7	91.0
24.0	100.0	100.0	100.0	100.0

Figure 3.--Rainfall distribution (7).

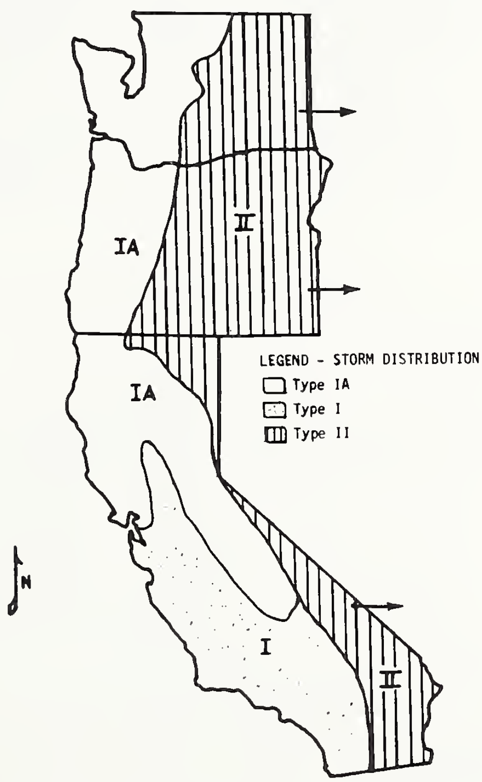


Figure 4.--Storm distribution regions in the western United States (8).

RAINFALL CHARACTERISTICS IMPORTANT FOR SIMULATION

G. D. Bubenzer[1]

INTRODUCTION

Simulate: 1. To give a false indication of, pretend, feign.
2. To have the external characteristics of, look or act like.

The above definitions imply both the goal and the frustration faced by researchers as they attempt to develop or improve rainfall simulators. The goal is a device which produces the rainfall characteristics of a natural storm. The frustration is knowing that the characteristics actually produced are false indications which do not accurately describe real-world phenomena. This frustration may arise from several sources. In some instances the rainfall characteristics of geographicsl regions may not be known in sufficient detail to allow accurate descriptions of erosive storms. Even when the rainfall characteristics are known, the researcher may not be able to find a device capable of reproducing all the desired characteristics. Finally, given the fact that the nozzle or drop forming device will not give the perfect simulation desired, choices must be made among the rainfall parameters to simulate, even though research has not yet clearly established the relative importance of each parameter. These choices must depend upon the nature of the project and criteria developed by the investigator.

This paper focuses on the characteristics of natural rainfall, with the assumption that simulators should be developed which duplicate these characteristics as nearly as possible. No attempt has been made to evaluate the relative importance of various characteristics for different types of erosion or infiltration research. For a discussion of this critical concern, the reader is referred to the article entitled 'Methods of attaining desired rainfall characteristics' by Meyer, which is included in these proceedings.

One of the first steps in the design of a rainfall simulator involves the development of a list of criteria to be met. Storm characteristics make up a portion of this list. A review of literature shows that six criteria related to storm characteristics recur.

1/Associate Professor, Agricultural Engineering Department, University of Wisconsin - Madison.

1. Drop size distribution similar to that of natural rainfall (Borst and Woodburn 1940, Meyer and McCune 1958, Bertrand and Parr 1961, Chow and Harbaugh 1965, Nassif and Wilson 1975, Shriner et al. 1977).

2. Drop velocity at impact near terminal velocity (Meyer and McCune 1958, Bertrand and Parr 1961, Nassif and Wilson 1975).

3. Rainfall intensity corresponding to natural conditions (Meyer and McCune 1958, Bertrand and Parr 1961, Chow and Harbaugh 1965, Shriner et al. 1977).

4. Uniform rainfall and random drop size distribution (Borst and Woodburn 1940, Meyer and McCune 1958, Bertrand and Parr 1961, Chow and Harbaugh 1965, Shriner et al. 1977).

5. Total energy approaching that of natural rainfall (Bertrand and Parr 1961, Munn and Huntington 1976).

6. Reproductive storm patterns (Meyer and McCune 1958, Bertrand and Parr 1961, Shriner et al. 1977).

The uniformity of agreement on the rainfall criteria for simulator development is further shown by the responses received from 28 developers or users of rainfall simulators. Two-thirds of the respondents using nozzle type simulators considered all of the first four criteria. More than 90 percent of all responses indicated that mean drop size, intensity, and uniformity of coverage were criteria used in selecting a simulator for their research. It appears, therefore, that the basic criteria for simulator development have been established and are generally accepted by developers and users of rainfall simulators. Drop size distribution, drop velocity at impact, and rainfall intensity appear as central to successful simulation.

BASIC PARAMETERS

Drop Fall Velocity

Laws (1941) made an extensive study of the fall velocity of water drops falling through still air as a function of drop size and fall distance (Table 1). Gunn and Kinzer's (1949) work, although obtained using a different experimental technique, substantiated Laws' data. The fall distance required to reach terminal velocity is dependent upon the size of the drop. For example, a 1.0 mm drop will reach terminal velocity after falling about 5 m, whereas a 4.0 mm drop requires more than 10 m free fall to reach terminal velocity.

Erosive rainstorms are often accompanied by significant winds. The actual impact velocity of the raindrop is a function of wind speed as well as drop size (Hudson, not dated, Van Heerden, 1964). Such effects are usually neglected in simulator design. Simulators designed on the

basis of Laws' data will represent minimum impact velocities of similar sized drops in natural storms.

Vegetation often intercepts a portion of the precipitation. Some of this precipitation coalesces on the tips of the leaves of the vegetation and free falls to the soil surface. Chapman (1948) showed that rain falling through a pine tree canopy had a larger drop size distribution than natural rain. These large drops may be of importance in soil erosion beneath tall canopies. Impact velocity of such drops can be determined using Laws' data when the coalesced drop size is known.

Adequate data are available for determining terminal velocity and the impact velocity of raindrops as a function of fall distance. Consideration of fall velocity is an especially important consideration in the design of simulators using drop formers. Because these drops have no initial velocity, large fall distances are required for the drops to approach terminal velocity. This limitation places severe constraints on the use of these simulators in achieving good simulation.

Drop Size Distribution

The median drop size and the drop size distribution of natural rainfall are dependent upon rainfall intensity. Reported relationships between mean drop size and intensity vary. Some researchers have used an exponential equation to express this relationship (Laws and Parsons 1943, Chapman 1948, Rogers et al. 1967). For example, the data complied by Rogers et al. (1967) appears to fit the exponential curve up to an intensity of about 50 mm/hr. At higher intensities it appears that the median drop size remains relatively constant. Carter et al. (1974) found a cubic equation best described this relationship for storms with intensities up to 254 mm/hr for the south-central United States. Data from Carter et al. (1974) also clearly indicated an increasing mean drop diameter through intensities of about 75 mm/hr at both the Holly Springs, Mississippi, and the Baton Rouge, Louisiana, location. The Holly Springs location appeared to follow the cubic formula more closely than the Baton Rouge site, which indicates a linear decrease in median drop size for intensities from 75 to approximately 200 mm/hr. McGregor and Mutchler (1976) developed a three term exponential relationship to relate the median drop size to intensity for the Holly Springs data. Their equation shows a rapid rise in median drop size for intensities up to about 40 mm/hr followed by a slowly decreasing drop size at the higher intensities. Hudson (1961) also found an increase in mean drop diameter for storms with intensities less than about 75 mm/hr with a slight decrease in mean drop size with further increases in intensity. Much of the reported differences may be attributed to wide random variation within and between storms, to geographical factors influencing storm type, and a lack of data at the high intensity levels. Despite this variation, the results indicate that there is a rapid increase in mean drop diameter with intensity for rainfall rates up to about 50 mm/hr. There is also strong evidence that at higher intensities the mean drop diameter tends to remain nearly constant or decrease slightly.

For many types of research, knowledge of the median drop size is not sufficient for the design of rainfall simulators. In cases where drop impact plays an important role in the erosion or infiltration process, it is important that the simulator drop size distribution be similar to that of natural storms. Typical drop size distributions for various locations throughout the United States are presented in Figures 1 and 2. Because of differences in methods of reporting, it is difficult to compare drop size distributions beween regions. Much of the apparent regional variation is probably due to random variation and differences in methods of grouping the data.

Because of the wide variation observed in the median drop size and the drop size distribution, it is difficult to establish a single guideline for design. The shaded area of Figure 3 can be used as a guide in selecting median drop size. Figure 4 shows a typical drop size distribution for rainfall rates over 25 mm/hr. Both of these curves are based upon the data of Carter et al. (1974), Rogers et al. (1967) and Laws and Parsons (1943) and upon the judgement of this author. Data for lower intensities showed wide variation in drop size distribution and were not included in the analysis (Table 2).

Rainfall Intensity

Selection of a design intensity for simulator development must depend upon the objectives of the investigator. Since the most severe erosion problems are usually associated with high intensity storms, most simulators have been designed to apply water at relatively high intensities. However, regional differences in intensity and storm characteristics must be considered before one accepts the concept of a Universal rainfall simulator. In some areas a major portion of the total annual soil loss may be associated with low intensity rain on thawing or snow covered fields. Such storms might contribute only a small portion of the annual soil loss in other parts of the United States, where major soil loss is associated with intense thunderstorm activity.

Most simulators in use today do not allow researchers to vary storm characteristics during a rainfall event. Temporal variations in intensity are known to have an effect upon both the amount and peak rate of runoff. The effect of this variation on soil loss is not well documented. Recent advances in simulator design will give researchers the opportunity to consider temporal intensity variations.

Impact velocity, drop size and intensity are not independent of each other. In nature the three are inter-related in a complex manner. Review of the literature indicates that the interaction is highly variable within and between storms and across geographic regions. Rainfall simulators are not designed to consider the dynamic nature of the rainfall process or its interactions. For example, intensity reduction on most simulators is controlled by reducing the percentage of the time the spray is striking the plot (Bubenzer and Meyer 1965, Amerman et al. 1970) or by reducing the number of nozzles spraying onto the plot (Swanson 1965). Average intensity is, therefore, reduced through intermittent or reduced appli-

cation, however, neither the impact velocity nor the drop size distribution is reduced at the low intensities as would occur in natural rainfall. This would appear not to be a serious problem until the intensity is reduced below 50 mm/hr.

Derived Parameters

Currently, simulators are not able to simulate the drop size distribution, impact velocity, and intensity of natural storms accurately. Several parameters derived from the basic units have been suggested for determining the erosivity of natural rainfall. Among the parameters most often used for comparision are kinetic energy per unit rainfall, momemtum per unit rainfall, kinetic energy per unit of drop impact area and momentum per unit drop impact area. Each of these parameters can be expressed in terms of the drop impact velocity and diameter (Meyer 1963). The erosivity of rainfall can therefore be expressed as:

$$E \propto d^a V^b$$

where: E is the rainfall erosivity

d is the drop diameter, and

V is the impact velocity.

The value of a and b are dependent upon the parameter chosen as a basis of comparison. The selection of the parameter used to describe soil erosivity is, therefore, critical in simulator design. Only as both the drop diameter ratio and the impact velocity ratio of the simulated and natural rainfall approach one (1) do all four parameters indicate close agreement between simulated and natural storms (Meyer 1963). The researcher must carefully choose among closely related parameters when simulating natural conditions. Unfortunately, none of these parameters has proven superior to the others. Rose (1960) and Hudson (1960) found the erosion was more closely correlated to momentum than energy for subtropical rainfall conditions. Garriels et al. (1974) found soil splash to be directly proportional to the kinetic energy. Bubenzer and Jones (1971) used multiple regression analysis with logarithmic transformed data to relate splash erosion to rainfall intensity and kinetic energy. At the lower energy levels, smaller drops produced significantly less splash than the larger drops even though the kinetic energy levels were nearly equal. As the energy level increased, the influence of drop size decreased. Gladiri and Payne (1977) reported that the breakdown of clods was closely related to dV^2 which has the same units as kinetic energy per unit impact area. Bisal (1960) reported sand splash to be related to $dV^{1.4}$. Engle (1955) also suggested that the erosion due to drops striking a metal surface was related to dV^2. Engel (1955) found that much of the erosion occurred along the perimeter of the drop and not at the center of the drop. If this is the case, it is possible that the erosivity could be related to the kinetic energy per unit of drop perimeter. Erosivity would then be proportional to d^2V^2.

Schottman (1978) used the parameter, dV^2, to consider the effect of small drops coalescing on leaves and falling to the earth as a large drop. Table 3 shows the relative erosivity, as measured by dV^2, of small drops coalescing to form a larger drop of equal mass when fall heights are sufficient for drops to reach terminal velocity. This data further indicates the need for accurate simulation of drop distribution and impact velocity of natural storms until the erosivity of rainfall in terms of an energy or momentum parameter is more clearly defined.

CONCLUSION

Meyer (1965) wrote, 'Until some measureable parameter is conclusively related to rainfall erosivity over a wide range of conditions, close reproduction of these two rainfall characteristics (drop size and impact velocity) seems essential.' This conclusion appears to be as valid today as it was in 1965. Numerous investigators have related portions of the erosion process to terms involving the various kinetic energy, momentum and intensity terms. However, no single parameter has surfaced as the best parameter to describe rainfall erosivity over a wide range of conditions. Perhaps because of the complexity of the erosion process and the interaction between rainfall, runoff, and soil erodibility, there is no single, simple parameter that covers a wide range of conditions. Until such a parameter is identified, researchers must determine the importance of the raindrop in the erosion or infiltration process being investigated. Where raindrop action is not of great importance to the process being studied, such an erosion or nutrient movement beneath an agronomic crop canopy or infiltration beneath a mulched surface, drop characteristics of the simulator may be of minor importance. However, when raindrop action is critical in the process, as in splash erosion or infiltration into an exposed soil, every attempt must be made to accurately simulate the drop size distribution, impact velocity and intensity of the natural erosive storms of the area.

REFERENCES

Amerman, C. R., D. I. Hillel and A. E. Peterson. 1970. A variable intensity sprinkling infiltrometer. Soil Sci Soc Amer Proc 34(5):830-832.

Bertrand, A. R., and J. F. Parr. 1961. Design and operation of the Purdue sprinkling infiltrometer. Purdue University Res Bul 723. pp. 16.

Bisal, F. 1960. Effect of raindrop size and impact velocity on sand splash. Can. J. Soil Sci. 40:242-245.

Borst, H. L., and R. Woodburn. 1940. Rainfall simulator studies of the effect of slope erosion and run-off. Soil Conservation Service. SCS-TP-36. pp. 32.

Bubenzer, G. D., and B. A. Jones, Jr. 1971. Drop size and impact velocity effects on the detachment of soil under simulated rainfall. Trans ASAE 14(4):625-628.

Bubenzer, G. D., and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans ASAE 8(1):73 and 75.

Carter, C. E., J. D. Greer, H. J. Braud, and J. M. Floyd. 1974. Raindrop characteristics in south central United States. Trans ASAE 17(6):1033-1037.

Chapman, G. 1948. Size of raindrops and their striking force at the soil surface in a Red Pine plantation. Trans Am. Geophy. Union 29:664-670.

Chow, V. T., and T. E. Harbaugh. 1965. Raindrop production for laboratory watershed experimentation. J. Geophysical Research 70:6111-6119.

Engel, O. G. 1955. Waterdrop collisions with solid surfaces. J. Res. Nat. Bur. Stand. 54(5):281-298.

Garriels, D., M. de Boodt and D. Minjauw. 1974. Dune sand stabilization with synthetic soil conditioners: a laboratory experiment splash erosion. Soil Sci 118(5):332-338.

Ghadiri, H., and D. Payne. 1977. Raindrop impact stress and the breakdown of soil crumbs. J. Soil Sci. 28:247-258.

Gunn, R., and G. D. Kinzer. 1949. Terminal velocity of water droplets in stagnant air. J. Meteor. 6(4):243-248.

Hudson, N. W. (not dated). The influence of rainfall on the mechanics of soil erosion with particular reference to southern Rhodesia. 3 vol. Unpublished MS thesis. Univ. of Cape Town, South Africa.

Hudson, N. W. 1961. Raindrop size distribution, kinetic energy and in-

tensity of subtropical rainfall. Proc. Inter-African Conference on Hydrology. Nairobi. pp 127-133.

Laws, J. O. 1941. Measurement of the fall velocity of waterdrops and raindrops. Trans. Am. Geophy. Un. 22:709-721.

Laws, J. O., and D. A. Parsons. 1943. Relation of raindrop size to intensity. Trans. Am. Geophy. Union 24:452-460.

McGregor, J. C., and C. K. Mutchler. 1976. Status of the R factor in northern Mississippi. In Soil Erosion Prediction and Control. Soil Sons. Soc. Amer. Ankeny, Iowa. pp. 135-142.

Meyer, L. D. 1963. Philosophy and development of simulated rainfall for erosion control research. ASAE Paper No. 63-724. Presented at the Annual Meeting of the American Society of Agricultural Engineers, Chicago, Illinois.

Meyer, L. D. 1965. Symposium on simulation of rainfall for soil erosion research. Trans. ASAE 8(1):63-65.

Meyer, L. D., and D. L. McCune. 1958. Rainfall simulator for runoff plots. Agr. Engr. 39(10):644-548.

Munn, J. R., and G. L. Huntington. 1976. A portable simulator for erodibility and infiltration measurements on rugged terrain. Soil Sci. Soc. Amer. J. 40(4):622-624.

Nassif, S. H., and E. M. Wilson. 1975. The influence of slope and rain intensity on runoff and infiltration. Hydrological Sciences Bull. 20:539-553.

Rogers, J. S., L. C. Johnson, D. M. A. Jones and B. A. Jones, Jr. 1967. Sources of error in calculating the kinetic energy of rainfall. J. Soil and Water Cons. 22(4):140-142.

Rose, C. W. 1960. Soil detachment by rainfall. Soil Sci. 89:28-34.

Schottman, R. W. 1978. Estimation of the penetration of high energy raindrops through a plant canopy. Unpublished PhD thesis. Agricultural Engineering Department, Cornell University, Ithaca, N. Y.

Shriner, D. S., C. H. Abner and L. K. Mann. 1977. Rainfall simulation for environmental application. Oak Ridge National Laboratory, Environmental Sciences Div. Pub. No. 1067.

Swanson, N. P. 1965. Rotating boom rainfall simulator. Trans ASAE 8(1):71-72.

Van Heerden, W. M. 1964. Splash erosion as affected by the angle of incidence of raindrop impact. Unpublished PhD thesis. Purdue University, West Lafayette, Indiana.

TABLE 1. Fall velocity of water drops in still air (Laws 1941)

Drop Diameter (mm)	Fall Distance (m)							
	1.0	2.0	3.0	4.0	5.0	6.0	8.0	20.0 (terminal)
	Fall Velocity (m/sec)							
1.5	3.64	4.50	4.99	5.25	5.39	5.47	5.51	5.51
2.0	3.83	4.92	5.55	5.91	6.15	6.30	6.35	6.58
2.5	3.98	5.19	5.89	6.34	6.67	6.92	7.22	7.41
3.0	4.09	5.37	6.14	6.68	7.08	7.37	7.75	8.06
3.5	4.15	5.52	6.35	6.95	7.40	7.73	8.15	8.52
4.0	4.21	5.63	6.52	7.17	7.65	8.00	8.46	8.86
4.5	4.24	5.72	6.66	7.36	7.85	8.21	8.70	9.10
5.0	4.27	5.79	6.77	7.50	8.00	8.36	8.86	9.25
5.5	4.29	5.85	6.86	7.61	8.11	8.47	8.97	9.30
6.0	4.31	5.90	6.94	7.69	8.30	8.55	9.01	9.30

TABLE 2. Percentage of total rainfall volume by size classes for different geographical locations and for rainfall intensities less than 25 mm/hr.

Drop Size Class (mm)	Geographical Location Urbana* Illinois 2.5 mm/hr	Washington** DC 2.5 mm/hr	Pullman**** Washington 6 mm/hr	Urbana* Illinois 12.7 mm/hr	Washington** DC 12.7 mm/hr	South Central*** United States 19 mm/hr
0.0 - 0.5	0.0	2.0	2.2	0.0	0.0	1.9
0.5 - 1.0	10.9	16.0	10.0	2.1	5.7	6.4
1.0 - 1.5	57.7	35.4	25.9	24.7	18.6	14.7
1.5 - 2.0	23.0	26.1	32.9	29.0	27.6	19.7
2.0 - 2.4	6.3	12.1	14.8	20.3	20.9	20.6
2.5 - 3.0	1.6	5.2	14.0	11.4	13.6	15.0
3.0 - 3.5	0.5	2.0	0.2	7.1	6.8	9.7
3.5 - 4.0		0.8		2.8	3.0	5.7
4.0 - 4.5		0.4		1.9	1.8	3.4
4.5 - 5.0				0.7	0.8	1.7
5.0 - 5.5					0.4	1.2

*From Rogers et al. 1967. Drops less than 0.5 mm diameter not included in analysis.
**From Laws and Parsons 1941. As presented by Rogers et al. 1967.
***Adapted from Carter et al. 1974.
****Unpublished data by McCool.

TABLE 3. Relative erosivity, as determined by dV^2, for individual drops to that of a coalesced drop of equal volume. (Schottman 1978)

Number of Drops	Relative Erosivity
2	0.64
3	0.48
4	0.40
6	0.30
10	0.10

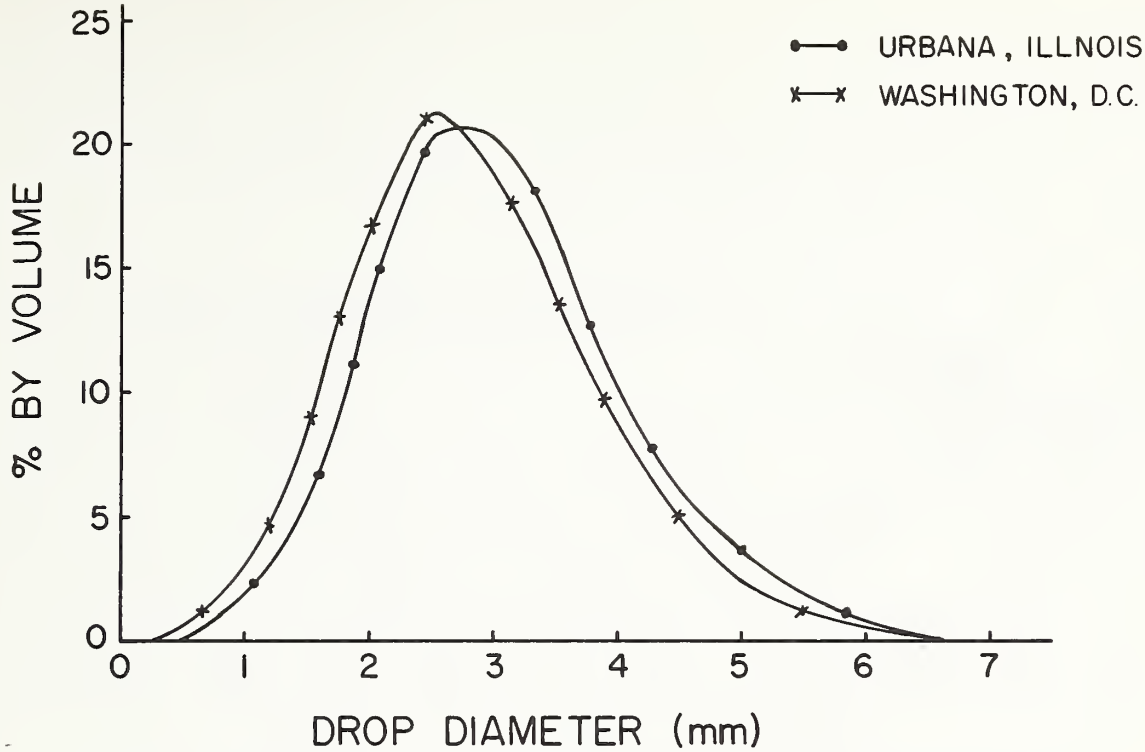


Figure 1.--Drop size distribution for two sites in the United States at an intensity of approximately 50 mm/hr.

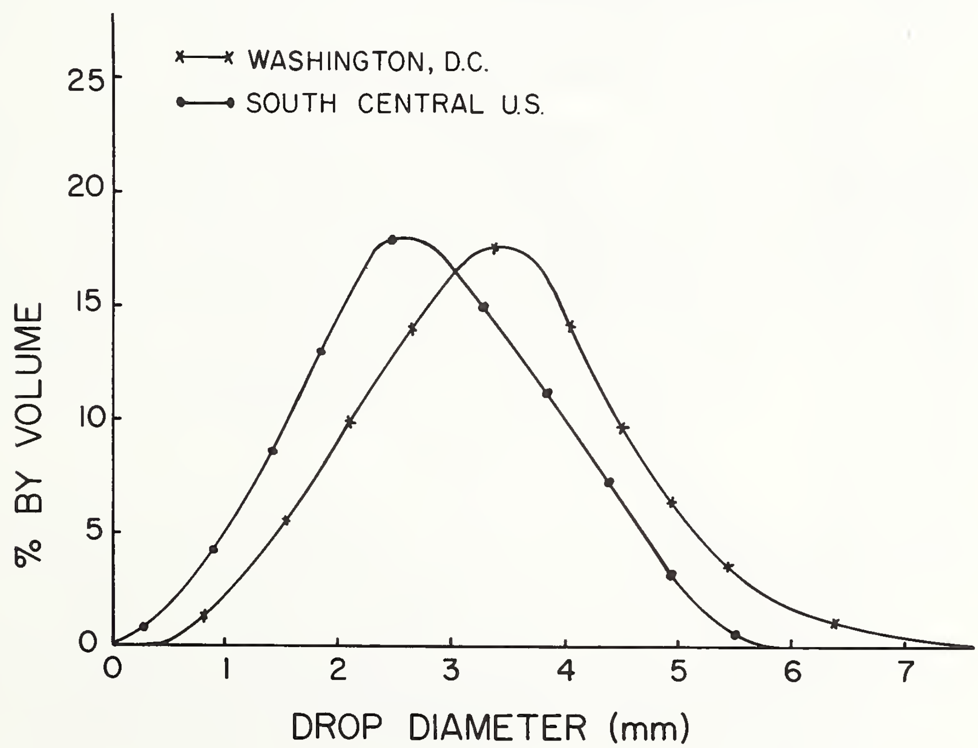


Figure 2.--Drop size distribution for two sites in the United States at an intensity of approximately 150 mm/hr.

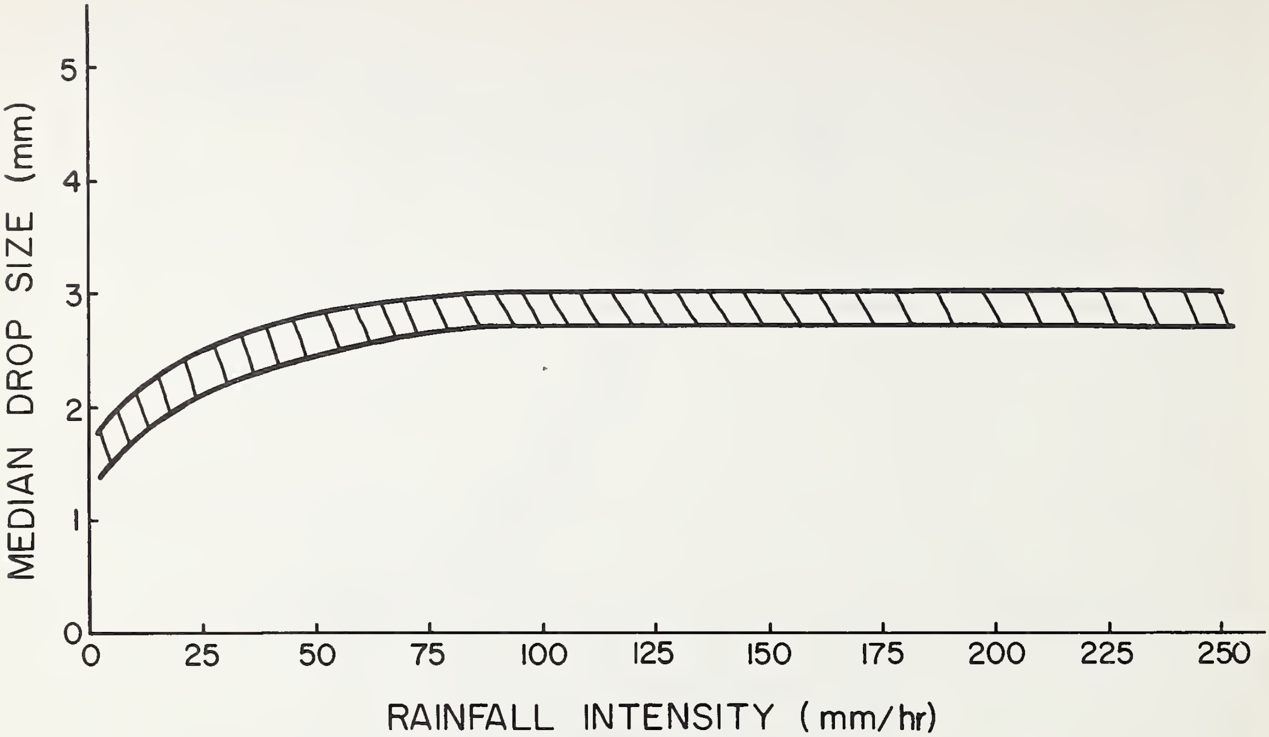


Figure 3.--Recommendations for median drop size for design of rainfall simulators.

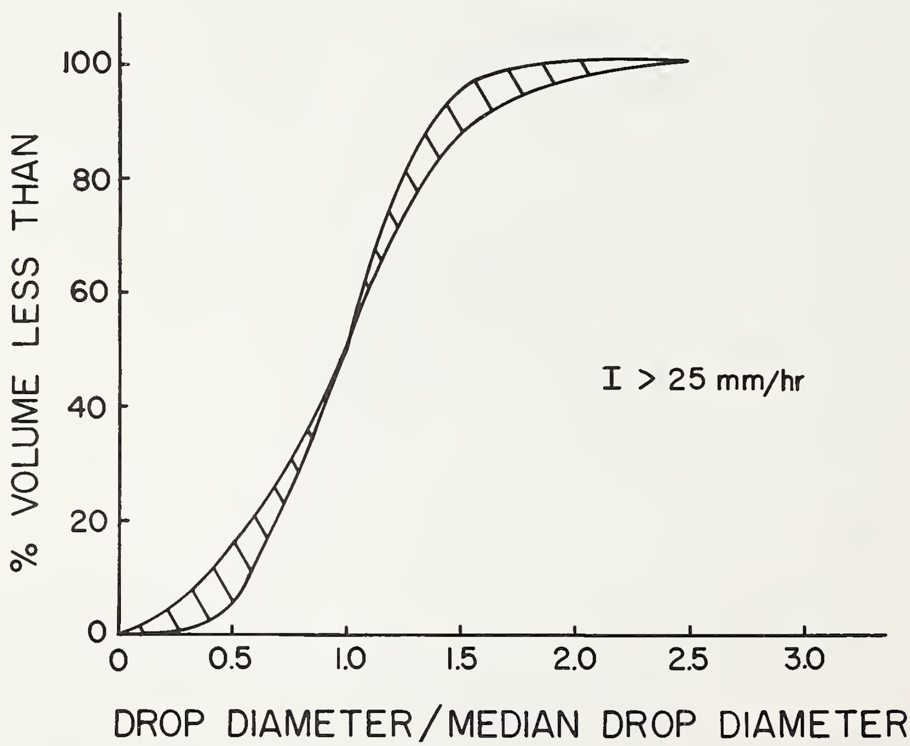


Figure 4.--Recommended drop size distribution for rainfall intensities greater than 25 mm/hr.

METHODS FOR ATTAINING DESIRED RAINFALL CHARACTERISTICS IN RAINFALL SIMULATORS

L. D. Meyer[1/]

Physical simulation of rainstorms is more difficult than many persons realize. The old adage "It's not nice to fool with Mother Nature" seems as appropriate here as anywhere. Major compromises are usually necessary before simulated rain is scientifically acceptable in comparison with natural rain. Consequently, some persons consider the use of simulated rain to be the wrong approach to obtaining research data or, at best, a "necessary evil" in such quests. Certainly, simulated rain is not the magic method for solving all research problems that some would like to believe. Yet it does have certain features (Meyer, 1965) that may be invaluable to a sound erosion/hydrology research program, since it usually provides more rapid results than natural rain; it can usually be conducted more efficiently from the standpoint of time and personnel; the conditions can be more carefully controlled; and the approach is more adaptable for certain types of studies. This paper discussed various techniques of rainfall simulation, characteristics that result from such techniques, and suitability of different techniques for different types of research.

METHODS FOR PHYSICALLY SIMULATING RAIN

Researchers have concocted a broad range of techniques and equipment for simulating rainfall (Meyer, 1958; Mutchler and Hermsmeier, 1965) during the last half century, ranging from walking up and down the slope with common sprinkling cans to elaborate, pushbutton-operated electronic and hydraulic machines. The major techniques used to produce simulated raindrops for erosion and hydrologic studies can be grouped into two rather broad categories: (a) those involving nozzles from which water is forced at a significant velocity by pressure and (b) those where drips form and fall from a tip, starting at essentially zero velocity.

Spray Nozzles

The simplest of the nozzles that have been used for rainfall simulation are the sprinkler cans, rose flares, and shower heads that are common in garden and household use. The spray from these methods is generally large drops at a very high rate of application.

1/ Agricultural Engineer, USDA Sedimentation Laboratory, Science and Education Administration, U. S. Department of Agriculture, Oxford, MS 38655.

Not many years after such techniques were first used, USDA researchers developed nozzles, such as Types D, E, and F, specifically for rainfall simulation. These generally produced drop sizes more similar to those of natural rainfall than did other available nozzles, but they were usually designed to spray upward or horizontally from a fixed position to reduce the application intensity at the ground surface. Such drops started their downward fall from a rather limited height, so their velocity at impact was usually low compared with the terminal velocity of raindrops.

During the past quarter century, the kinetic energy of rain at impact has been used as a major rainfall parameter (Wischmeier and Smith, 1958) and thus has made drop impact velocity an important characteristic to simulate. To attain higher impact velocities, spray nozzles, often those commercially available, have been pointed generally downward to take advantage of the initial nozzle velocity, or they have been positioned at great heights. To reduce the intensity, such nozzles are often moved to cover a much larger area than that covered when stationary, and/or a collector is positioned beneath the nozzles to intercept part of the spray. Generally, commercial spray nozzles have a wide distribution of drop sizes, and the drop sizes become larger as the orifice becomes larger and as the pressure is decreased.

A variation to the use of commercial nozzles is the use of rotating irrigation sprinklers, either part circle or full circle. This approach leaves much to be desired from the standpoint of velocity of fall, angle of impact, drop size distribution, intensity distribution, wind interference, and prolonged duration of intermittency, but it has potential for very large areas.

Other nozzles have included perforated pipe and rotating disks, but these methods have rarely been employed in rainfall simulation for erosion or hydrologic research.

Drips from Tips

Another common approach has been the formation of drops on the tip of a material until the weight of a drop overcomes its surface tension to the drop former and the drop falls. Early forms of this approach used short lengths of yarn hanging through holes in the bottom of a water container. More recently, hollow glass tubes, hypodermic needles and plastic tubing have been used. Rate of drop formation is controlled by the length of tubes, the diameter of the tubes including multiple diameters, and/or airtight modules into which flow or pressure are controlled.

Successive drops that form on a tip are generally identical in size, although different types and sizes of tips produce different sized drips. The size range for simulated drops formed in this manner is usually between 2 and 5 mm in diameter. Since such drips begin their fall with no velocity, the formers must be located quite high above the impact surface to reach near the drops' terminal velocities. Also, such drop formers must be spaced within a few centimeters of each other to obtain satisfactory intensity distributions, so the drip method is very difficult to use on areas larger than a few square meters.

CHARACTERISTICS OF RAINFALL SIMULATORS

To simulate the characteristics of natural rainstorms, certain characteristics are desirable for rainfall simulators. Some of the more important for those used in hydrologic and soil erosion research include most or all of the following:

(1) Drop size distribution near that of natural rainstorms

(2) Drop impact velocities near those of natural raindrops

(3) Intensities in the range of storms for which results are of interest

(4) Research area of sufficient size to satisfactorily represent the treatments and conditions to be evaluated

(5) Drop characteristics and intensity of application fairly uniform over the study area

(6) Raindrop application nearly continuous throughout the study area

(7) Angle of impact not greatly different from vertical for most drops

(8) Capability to reproduce the rainstorm durations of interest at selected intensities

(9) Satisfactory characteristics when used during common field conditions such as high temperatures and moderate winds

(10) Portability for movement from research site to site

These important characteristics vary for different methods of rainfall. Some of the major characteristics in relation to the different methods of rainfall simulation are as follows:

Drop size

Natural rainfall consists of a wide distribution of drop sizes that may range from near zero to about 7 mm in diameter. Raindrop sizes increase with rain intensity up to a certain intensity and then tend to remain the same.

Drip-type rainfall simulators generally have a very limited range of drop sizes and often consist of only one size. Nozzles have a much wider size distribution, with the drop size generally increasing with larger nozzle orifices and decreasing with larger pressures. Nozzles that spray horizontally frequently have finer drops near the nozzle and larger drops as the distance from the nozzle increases. Spray that periodically intersects a collector will have some of the drops broken into finer drops by the collector edges.

Drop Velocities

Raindrop fall velocities vary from near zero for mist-sized drops to more than 9 meters per second for the largest sizes. A common sized drop of 2 mm falls between 6 and 7 m/sec.

Velocities of drops from formers depend largely on the height of the former but somewhat on the drop diameter, since larger drops accelerate faster, but smaller drops have lower terminal velocities. The impact velocity of drops sprayed upward or horizontally from nozzles depends on the height at which the vertical component of velocity is zero, because from there they behave like those from drop-formers. For nozzles that are pointed downward, orifice velocity increases with greater pressure, but greater pressure reduces drop sizes. When downward-spraying nozzles produce drops at greater than their terminal velocities, these drops slow toward their terminal velocities during the distance of fall from the nozzles. When nozzle velocities are less than terminal velocities, the drops accelerate during their freefall. When the nozzle velocity is less than terminal velocity for the larger drops but greater than terminal velocity for the smaller drops, both sizes tend toward their terminal velocities during the fall distance.

Rainfall Energy

The kinetic energy at impact is the characteristic most often used to compare rainfall simulators with natural rain. Basic physics suggests that it should be an important parameter, and Wischmeier (1959) and others have shown that it or the similar momentum parameter is important. However, the area over which this energy or momentum is dissipated at impact may also be important. For example, it takes eight drops of 2 mm diameter to equal the mass of one 4 mm drop, but the cross section of eight 2 mm drops is twice that of a 4 mm drop. The kinetic energy or momentum of the 2 mm drops, although probably somewhat less due to slower velocity, will be dissipated over twice the area. Thus, the erosiveness of 4 mm drops may be much greater than for 2 mm drops of the same kinetic energy or momentum. Recent unpublished results indicate that large drips falling at low velocities from cotton leaves were nearly as erosive as smaller, much higher velocity simulated raindrops of the same mass. Such findings support the belief that kinetic energy or momentum alone is not an adequate parameter for comparison.

Further discussion of various possible parameters of comparison is given by Meyer (1965). The conclusions reported there still seem appropriate: "...until some parameter is proved to be adequate for comparison, this analysis suggests (a) that both the drop-size distribution and drop-fall velocity of natural rainfall should be simulated as closely as possible and (b) that an appreciable sacrifice of either for the other is unwise. One of the parameters may be chosen as a guide, but its influence should be secondary to a comparison with actual raindrop characteristics."

Rain Intensities

Intensities of rainfall vary from almost zero to several hundred millimeters per hour. Generally, very low intensities are not of major interest for erosion and hydrologic studies, and very high ones are so rare that they may be of limited interest. However, intensities of about 10 to 100 mm per hr. occur quite commonly and thus are of greatest importance.

Intensities from drop formers are varied by restricting the flow rate to the former and by the spacing of the formers. Where the pressure on the water source to the former can be varied, flow control of resultant intensities can often be achieved over rather wide ranges without varying the number or size of the formers.

Nozzle intensities vary with the orifice diameters, the hydraulic pressure on the nozzles, the spacings of the nozzles, and the movement of the nozzles to cover larger areas than if operated stationary. Movement of the nozzles generally results in intermittency of application, however. An alternative to moving the nozzles is moving a collector in and out beneath the nozzles to intercept some of the spray.

Intensity Variation During Storm

Intensities of rainfall vary widely during most rainstorms, both with time and space. The capability to vary the intensity during simulated rainstorms may seem desirable, but this is difficult to achieve with many types of equipment. Variation of intensities from drop formers is generally achieved by varying the pressure or water flow to the tips. For nozzle-type equipment, intensity variation is accomplished by changing the area covered per nozzle or by varying the duration between applications. Even if variations in rainfall intensity during simulated rainstorms can be simulated, the combination of intensities and durations to use is difficult to select. A researcher should seriously consider whether the effort can be justified, whether a specific variable-intensity storm can be identically simulated for all treatments, and whether the resulting data can be meaningfully interpreted.

Intermittency of Application

Rainfall on any point is intermittent, but in a random sense. Rainfall simulators with intermittent application often alternate momentary high-intensity applications with no application over a considerable area for an extended period. Certainly, intermittency of rainfall application is to be avoided, if possible, and minimized in all instances, but intermittency often is necessary because nozzles have not been found that do a good job of rainfall simulation when operated in a stationary position. Intermittency is generally necessary so that nozzles may be moved to cover a greater area and thus reduce the intensity or so that part of the spray from the nozzles may be intercepted before it strikes the plot. Drop-former methods of rainfall simulation usually are intermittent in a random fashion similar to rainfall.

Direction of Spray Movement

For nozzles that move, their short duration, high intensity spray usually follows a certain path. When this path is up plot or down plot, it can affect the hydraulics of runoff and consequently the sediment transport. Generally, spray movement across the plot has less effect.

Direction of Drop Impact

Rain often falls with a horizontal component of velocity due to wind. The direction usually varies from storm to storm, but may average near vertical for the entire year. The effect of wind on rainfall impact has been studied, but generally, raindrop impacts that are nearly vertical are the only type that can be reasonably simulated in a controlled manner that is uniform over the entire area. Drops from drop formers nearly always fall vertically, and drops from most nozzles that are directed downward or are located at considerable heights also fall near vertical. However, drops from nozzles that have high initial horizontal velocities and are located at small heights may have appreciable horizontal velocities.

Other Characteristics

Natural rainfall has other characteristics that may affect results and thus might be simulated for rainfall simulator research. These include drop (and soil) temperature and drop shape at impact, but they, like drop impact angle, are rather subtle differences for most research goals. Their effects may be studied under special conditions, but generally cannot be controlled for most studies. The addition of unreasonable or unnecessary sophistication to criteria for rainfall simulation studies may seriously complicate the research and limit the amount of data that can be obtained.

HOW RESEARCH GOALS DETERMINE PREFERRED RAINFALL SIMULATOR CHARACTERISTICS

The ideal rainfall simulator would be inexpensive to build and operate, would simulate rainfall perfectly, would be simple to move, and could be used whenever and wherever needed. Most researchers realize that such a utopian rainfall simulator is an impossibility, so different rainfall simulators have different characteristics because the research goals are different. Each researcher must recognize the great importance of assessing his research situation so as to properly identify those characteristics of greatest importance. Available or conceived designs need to be compared with the preferred characteristics to evaluate their suitability. Where possible, operating rainfall simulators should be extensively observed as part of the selection process. Where suitable equipment or designs are not available, the researcher could greatly benefit from consultations with researchers who are experienced in simulated rainfall research before embarking on a rainfall-simulator development program.

Some of the research conditions and goals that influence the selection of appropriate simulated rainfall techniques and equipment include the following:

Test area--Rainfall simulators have been used on "plots" ranging in size from small cans to greater than a hectare. On areas up to several square meters or so, rather elaborate methods of rainfall simulation such as drop formers may be feasible, but these methods are not feasible on areas of dozens or hundreds of square meters. For such areas, nozzles that each cover a considerable area are usually much more practical.

Research plots should be wide enough to realistically test the treatment characteristics. They should be long enough to accumulate rates of runoff that are capable of transporting sediment in a manner typical of the treatment.

Type of erosion or infiltration--When the erosion rate or infiltration rate to be studied is significantly affected by raindrop impact, the impact characteristics of rainfall must be adequately simulated. Evaluation of interrill erosion cannot be done properly unless rain impact characteristics are similar to those of appropriate rainstorms, and infiltration rates cannot be properly evaluated on soils that seal from raindrop impact unless the simulated rain acts on these soils in the same manner as natural rainfall.

However, results from small areas that are suitable for evaluations of interrill erosion and localized infiltration cannot be simply extrapolated to larger areas where flowing runoff would cause rill erosion or where other characteristics occur that may greatly affect infiltration rate. For such conditions, rainfall simulators must apply rainfall to large enough areas so that runoff can accumulate or so that land irregularities affecting infiltration can be properly evaluated. For such larger area studies, elaborate equipment that might be suitable on small areas will probably not be suitable.

On soils or topographies where gully erosion or subsurface flow may be major considerations, research areas may need to be quite large. For such studies, it may be most important to apply water relatively uniformly over a very large area, even if it means sacrifice in the impact characteristics. Agricultural irrigation equipment then may be the only feasible approach, particularly when there is cover on the soil surface, and may adequately test those erosion or infiltration characteristics of primary interest.

Comparative versus quantitatively accurate results--Some research seeks to accurately evaluate erosion or infiltration quantitatively, whereas other research is primarily concerned with comparisons among several treatments. For quantitatively accurate results, major rainfall characteristics such as drop size, impact velocity, and intensities must be nearly identical to those of rainfall. However, where comparison of several conditions is the primary goal, studies at one or a limited number of intensities and some compromise in drop characteristics may be acceptable. However, the researcher should clearly distinguish for himself and others the quantitative accuracy of his results.

Magnitude of differences among treatments tested--Research with simulated rainfall, particularly when conducted under field conditions, will have considerable unexplained experimental variations. Thus, research should not be attempted where only minor or subtle differences are expected, because any differences found will probably not be significant, either statistically or realistically. Studies with simulated rain should primarily attempt to test conditions of major importance that may be expected to have perceptible differences in the data to be obtained.

Plot condition--Characteristics of the research plot often affect the suitability of the simulated rainfall. Where the soil surface of all treatments is well covered by plants, mulches, or other surface covers, the impact energy of the simulated rainfall will be of minor importance as far as erosion and infiltration are concerned, although it may affect the runoff hydrology of the study. Where tall crops such as mature corn are growing, the height of the drop former or nozzle and the type of nozzle movement may affect the suitability of the resulting simulated rain. Where the surface of the plot has a very steep slope and the rainfall simulator is designed to apply all simulated rain from the same elevation, the impact energy and intensity distribution may vary excessively from the upper end to the lower end of a long plot.

Water supply--Rainfall simulators require a water supply of adequate quantity and quality for the purposes of the study. For some rainfall simulators and certain conditions, adequate water can be hauled to the site, but where this is done, collection of most unused water is often quite important. Research on larger areas may require a pond, lake, or stream with great volumes of available water, so some waste may not be a problem.

Where studies of the chemistry of runoff are included, the water must be of good quality and should be evaluated during simulated rainstorms. Even where water quality resulting from runoff or infiltration is not being evaluated, water sources that contain certain chemicals or organics should be avoided because of their possible effects on soil stability, sealing, or infiltration.

Handling convenience--Research that is primarily conducted at one or only a few locations may be able to contend with a rainfall simulator that is rather difficult to assemble, disassemble, and transport. However, when experiments are planned at numerous locations, the ease of handling becomes very important. Also, bulky and complex equipment cannot be handled satisfactorily by a 1- or 2-man research team.

Cost, safety, etc.--The importance of considering cost, safety, and other such aspects of rainfall simulators is obvious, but sometimes certain aspects are overlooked. For instance, the initial cost of the materials for a rainfall simulator may be quite minor compared to the commitment of time to construct and test it plus the effort required to operate it, maintain it, and process the resulting samples. A simulated rainfall research program should not be undertaken unless

administrative commitment is obtained for continuing expenses and personnel during some years to come.

Other criteria could be added that should be considered in determining the preferred rainfall simulator characteristics for specific research goals. Those listed simply illustrate some of the concerns that a researcher should have during the planning stages. But the greatest question to be faced is: Can the conditions of interest be adequately evaluated using simulated rainfall? Unless that can be answered positively with considerable assurance of success, a rainfall simulator can be more of a burden than an asset to a research program. On the other hand, where rainfall simulators are applicable, they can be marvelous research tools in hydrologic and erosion research.

CLOSING COMMENTS

Even with all of the problems and limitations that rainfall simulators bring to research programs, many of us probably would be amazed at the high percentage of useful erosion, runoff, and infiltration knowledge that has been obtained during the past 20 years from simulated rainfall studies. While simulated rainfall is not a magic method for satisfying all research needs, it often is the only way that research can be feasibly conducted. Many research studies could never be even considered if they could not be conducted using simulated rainfall.

Good, usable data has become a critical need in many phases of soil and water management, both for research progress and for implementation of water quality and resource conservation activities. Everyone seems to be clamoring for data, and much past data is not suitable. As this need intensifies, rainfall simulators will undoubtedly be widely used to obtain needed data. For this reason, simulated rainfall will probably continue to be used and even grow in importance for future hydrologic and erosion research. The researcher has a big responsibility to use research equipment and techniques that will produce reliable data.

REFERENCES

(1) Meyer, L. D.
1958. An investigation of methods for simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles. USDA-ARS Special Report No. 81, 43 pp.

(2) Meyer, L. D.
1965. Simulation of rainfall for soil erosion research. Transactions ASAE, 8:63-65.

(3) Mutchler, C. K. and L. F. Hermsmeier.
1965. A review of rainfall simulators. Transactions ASAE, 8:68-69.

(4) Wischmeier, W. H.
1959. A rainfall erosion index for a universal soil-loss equation. Soil Science Society of America Proceedings. 23:245-249.

(5) Wischmeier, W. H. and D. D. Smith.
1958. Rainfall energy and its relationship to soil loss. Transactions American Geophysical Union, 39:284-291.

A PROGRAMMABLE RAINFALL SIMULATOR FOR FIELD PLOTS 1/

G. R. Foster, F. P. Eppert, L. D. Meyer 2/

EVENTS LEADING TO THE DESIGN

Since the late 1950's, the Erosion Research Unit of the U. S. Department of Agriculture, Science and Education Administration (USDA-SEA) at Lafayette, Indiana has successfully used a field plot rainfall simulator known as the rainulator (Meyer and McCune, 1958). Following construction of the Lafayette rainulator, the Morris, Minnesota and Watkinsville, Georgia SEA locations made significant improvements to the rainulator without changing its basic design (Hermsmeier et al., 1963). Swanson (1965) at the Lincoln, Nebraska SEA location made a major design change when he built a rotating-boom rainfall simulator using the same nozzles as those on the rainulator.

During the 60's and 70's, numerous improvements in the original rainulator design were identified. Minor changes were made, but major improvements were not made because of time and financial limitations and the urgency for soil erosion data.

In 1977, the Lafayette SEA location decided to extensively update its rainulator. Since updating was perceived to be a design problem, SEA contracted with a professional engineering firm rather than with a research group for the redesign. Funds were provided by the Lafayette location and the North Central Region of USDA-SEA.

Before a design firm was identified, written design criteria were prepared by SEA personnel at Lafayette and Peoria, Illinois and reviewed by SEA scientists who have used rainfall simulators in experimental infiltration and soil erosion research. Subsequently, Booker Associates, Incorporated, St. Louis, Missouri was contracted through Federal procedures for procurement of engineering services. Booker began the project by visiting the Lafayette, Watkinsville, Georgia and Oxford, Mississippi SEA locations for onsite discussions of problems with current rainfall simulators and potential ideas to incorporate in a new simulator. Based on the criteria, Booker submitted an initial design concept in December, 1977. After review by SEA researchers at Watkinsville, Morris, Lincoln, Oxford, and Lafayette, the original criteria were revised to correct deficiencies and to define areas which were unknown when the original criteria were written.

Given the revised criteria, Booker developed the design discussed below. Several formal and informal review sessions were held between USDA-SEA and Booker over the course of the design. W. E. Peffer, Mechanical Engineer, North Central Region, Peoria, Illinois; L. D. Meyer, Technical Advisor for Erosion,

---

1/ Contribution from the Soil, Water, and Air Science, North Central Region, Science and Education Administration, USDA in cooperation with the Purdue Agricultural Experiment Station. Purdue Journal No. 7627

2/ Hydraulic Engineer, USDA and Assistant Professor, Agricultural Engineering Department, Purdue University, Lafayette, IN; Project Leader, Booker Associates, St. Louis, MO; and Agricultural Engineer, USDA-Sedimentation Lab, Oxford, MS.

Oxford, Mississippi; and G. R. Foster, Hydraulic Engineer, Lafayette, Indiana evaluated progress and gave Booker guidance. F. P. Eppert was Booker's project leader for the contract. The design was completed in late 1978. A portion of the simulator is now under construction.

DESIGN CRITERIA

The design criteria identified deficiencies in the Lafayette rainulator and outlined specifications for the new simulator.

The following deficiencies were identified.

1. Cycle time of about 20 seconds was too long for studies of infiltration and overland flow hydrology. Cycle time is the time lapse between nozzle passes over points on a plot that receive water least frequently.
2. Easily varied intensities in space and time were impossible.
3. The rainulator would not operate satisfactorily on slopes steeper than 20%. Other locations had modified their rainulators for slopes as steep as 40%.
4. Mechanical and electrical reliability was poorer than desired.
5. Equipment was complex to set up and operate.

Although improvements by others to the rainulator eliminated some of these deficiencies, cycle time had not been reduced and variable intensity in space or in time with a fine resolution was still not available. Rainulators are limited to intensities of 1 1/4, 2 1/2, and 5 in/hr.

The 80100 Vee Jet nozzle was originally selected for the rainulator because it closely simulated natural rainfall within the mechanical constraints of the rainulator (Meyer and McCune, 1958). Its energy level is about 75% of that of intense natural rainfall, and its drop distribution is close to that of natural rainfall, characteristics important for erosion research. Comparison of data collected from rainulators with that from natural rainfall substantiated that the rainulator nozzle produces acceptable results for erosion studies (Barnett and Dooley, 1972; Young and Burwell, 1972). More recently, Meyer and Harmon (1977) found that the energy level of the 80150 Vee Jet nozzle is very close to that of natural rainfall for Northern Mississippi. Therefore, the new simulator was to use either the 80100 or 80150 nozzle. Use of the 80100 nozzle will permit a direct comparison of the new simulator with the rainulator.

In addition, the criteria defined the following major specifications.

1. Cycle time would be 1 sec or less for design intensities of 1 1/4, 2 1/2, and 5 in/hr.
2. Operate over 12 ft wide plots having lengths up to 155 ft.
3. Easy assembly and disassembly by 2 people using simple tools.
4. Operate on slopes as steep as 3:1.
5. Reduced number of hose connections during assembly and disassembly.
6. Improved mechanical and electrical reliability.

The design problem evolved as one of either modernizing the basic rainulator design or designing an entirely new mechanism using rainulator nozzles. The direction was resolved after initial input from Booker.

DEVELOPMENT OF THE DESIGN

Main Concepts

Booker used value engineering to evaluate various design concepts. Although the rainulator nozzle specified in the criteria requires intermittent application and moving nozzles, stationary, continuous flow nozzles were considered. Even though a nozzle manufacturer assured us of the availability of nozzles having the median drop size and energy level of natural rainfall at given intensities, we chose not to use them. First, a given nozzle is restricted to a very narrow range of intensities. Varying pressure to adjust intensity by changing nozzle flow rate alters drop size distribution, spray pattern, and spatial distribution of intensity. Second, nozzles have hard spots, areas of locally high intensities, which require careful overlapping for spatially uniform intensity. Intensities in the directions of motion for moving nozzles are as uniform as the velocity of the translating mechanism.

Energy per unit of rainfall is constant for all intensities when nozzle flow rate is the same for all intensities. This is not a serious limitation because energy per unit of rainfall varies little with intensity at intensities above 1.0 in/hr (Wischmeier and Smith, 1978; McGregor and Mutchler, 1977). Given these considerations, intermittent application was accepted and in fact provides a good method for varying intensity. Also, the rapid intermitency concept was proven in smaller simulators (e.g., Bubenzer and Meyer, 1965; Grierson and Odes 1977; Meyer and Harmon, 1977).

Two ways of obtaining intermittency were considered: (1) periodically turn each nozzle on and off or (2) periodically deflect flow from a continuously flowing nozzle. The first method was rejected because operation time for typical solenoid valves and control systems seemed too slow for higher intensities. Furthermore, sand and other foreign material could clog valves, a problem which we wished to eliminate from the rainulator.

The fan pattern of the rainulator nozzle requires that it either be translated or oscillated to cover its application area. After considering various translating mechanisms including a revolving carriage, revolving nozzles, rotating nozzles, and moving frames, we chose an oscillating mechanism for its simplicity and low inertial forces. High inertial forces are a problem with the rainulator if cycle time is reduced below 20 seconds. A three nozzle rainfall simulator for laboratory erosion research had previously proven this concept (Bubenzer and Meyer, 1965).

With this concept, the nozzles flow continuously and oscillate from side to side where they briefly rest. When a nozzle is to the side, flow is deflected from the plot area. Periodically, the mechanism is energized, and water sprays on to the plot as the nozzles pass between deflectors. Intensity is controlled by controlling the frequency that a nozzle pass between its deflectors. A one nozzle simulator of this design works satisfactorily for laboratory and field interrill erosion research (Meyer and Harmon, 1977).

At this point, we realized that rainfall simulator design is a compromise. The final design depends on the application and the preference of those charged

with making final design decisions. Cost, simplicity, ease of use, and reproducibility of important rainfall parameters are all important factors. The oscillating concept is such a compromise.

Since drop trajectory from the nozzles is curved, crop canopy intercepts drops which reduces intensity on an area midway between adjacent nozzles. This area is about 0.57 ft wide for a 3 ft high canopy and a nozzle height of 8 ft and lateral spacing of 3.6 ft. Raising the nozzles and reducing their spacing minimizes the problem. However, since canopy was greater than 6 in high in only one study in the last 10 years at Lafayette, we decided that this was not a major concern. In order to maintain a reasonable trajectory, the criteria specified that the effective width covered by a nozzle sweep could be no more than 4 ft.

Flow from oscillating nozzles is usually deflected and collected for recirculation after the spray passes beyond the study area (Bubenzer and Meyer, 1965 and Meyer and Harmon, 1977). That is not possible in this application. The center of spray patterns from two laterally adjacent nozzles must meet at the plot surface. The design trajectory, based on a 2.25 mm median drop size, a nozzle exit velocity of 22.3 ft/sec (Meyer, 1958)*, a spherical drop and drag forces, was defined as the center of the spray pattern.

Basic Trough Assembly

The next step was to design a system of deflectors, water collectors, nozzle mountings, and actuating mechanisms. The basic design width is 18 ft (12 ft plot width plus 3 ft of border on either side of the plot). Limiting the number of nozzles reduces the total (not net) quantity of water that must be pumped. Since 4 nozzles exceeded the 4 ft spacing criteria, 5 nozzles per 18 ft at 3.6 ft apart were used.

The nozzles are mounted in an across-slope trough and oscillate laterally across slope. Excess (i.e., deflected) flow is collected and routed to one end of the trough for recirculation. Having the nozzles spray along the length of the trough rather than toward the side minimizes splash out of trough openings. Deflectors surrounding holes in the bottom of the trough deflect the nozzle flow and keep excess water from overflowing onto the plot. Instead of a sharp edged deflector which could cut an operator servicing the troughs, 18 gage sheet metal cut square was chosen for the deflector.

Excess water must flow to one end of the trough with the trough on a zero lateral slope and tilted anywhere from a zero slope up to a 3:1 slope. Based on a channel width of 9 in between the ends of the deflector and the trough side walls, and a Manning's n of 0.012, the slope of the energy gradeline was estimated to be 0.003 for the maximum discharge of 20 gpm (i.e., 5 times 4

---

* Meyer and Harmon's (1977) more recent data and manufacturer literature suggest a higher exit velocity of 25 to 29 ft/sec. Also, Meyer and Harmon's data suggest that the median drop diameter for the 80100 nozzle may be as small as 1.3 mm. We became aware of these data after the design was completed. Modifications can be easily made in the constructed simulator.

gpm/nozzle at the 6 psi design pressure). The estimated maximum flow depth was 1.35 in, while 1.5 in was measured in a prototype. The height of the deflectors was set at 3 in.

Flow at the nozzle exit is a continuous stream and does not break into drops until some distance from the nozzle. The deflectors should be located where the flow has broken completely into drops. From photographs, we determined that drop breakup is not complete until about 5 in from the nozzle. However, adverse effects of the deflectors significantly decrease by 2 in. Locating the deflectors 3 in from the nozzle is an acceptable compromise. A greater distance increases trough height and thus its weight and volume. Angling the deflectors to the nozzle flow by 8 degrees prevents direct spray onto the underneath side of the deflector and minimizes dripping onto the plot.

The width between the upper edges of the deflectors is determined from the design drop trajectories required to cover 3.6 ft of plot width at the ground. The computed included angle of the trajectories is 33 degrees which gives a width of 3.55 in between the deflectors for a nozzle exit 3 in from the deflector and 3.25 in from its center of rotation. The nozzle adjusts up and down to obtain uniform intensity between laterally adjacent nozzles.

Continuously flowing nozzles require recirculating 94, 88, and 77% of the flow for the 1 1/4, 2 1/2, and 5 in/hr intensities, respectively. Two recirculating possibilities were considered. The first was to allow excess water to drain by gravity to a 1000 gallon holding tank. The simulator pump located at the holding tank would pump the application rate times application area plus the excess return water. This amounts to 640 gpm for 5 in/hr and 4 - 12 ft by 35 ft plots. Excess water would not rapidly drain back to the holding tank when slopes are flat. Also, a large, inconvenient, return pipe would be required.

The second plan, which was accepted, was to attach a 6 in deep sump to one end of each trough to collect the excess water within each trough. A submersible pump (1/3 hp, 30 gpm at 20 ft of head for the 80100 nozzles) in the sump supplies water to the nozzles in each trough. Makeup water for spray onto the plot enters the sump through a short coupled float valve which maintains a constant water level in the sump. In place of one large pump at the holding tank, a 45 kw generator is required to drive the 32 individual pumps of the planned 4-plot (12 ft by 35 ft) full-sized simulator. The return pipe is eliminated. Furthermore, nozzle pressure in any single trough can be adjusted without affecting any other trough. Pressure is set with a ball valve just downstream from the sump pump. A pressure gage is located between the second and third nozzles in the 1 1/2 in main supply line.

Piping within the trough is conventional schedule 40 PVC. A straight, swivel joint connects the oscillating nozzle assembly to the supply line. The swivel joint has a simple, sliding bearing rather than ball bearings because ball bearings might stick from water seeping past the seals.

The oscillating mechanism is a simple crank, lever, and connecting link system. The 2 7/8 in lever arm of each nozzle assembly is connected to the other lever arms in the trough by a connecting link. The drive crank radius of 2 in gives a total oscillation angle of 92 degrees at the nozzle.

Intensity Control

When the drive crank turns continuously, intensity is approximately 5.3 in/hr. For 1 1/4 in/hr intensity, the nozzle sweeps in one direction once every 0.9 sec while the nozzle passes 4 times (twice in each direction) every 0.9 sec for 5 in/hr. A 100 rpm, 110 vac, 1/15 hp gearmotor drives the crank at 133 rpm through a 1.33:1 speed increasing roller chain drive.

The frequency that the nozzle passes over the trough opening is controlled by periodically engaging the crank with a combination electro-mechanical clutch-brake. A 110 vac input pulse engages the clutch by raising a pawl from a stop. Response time is about 27 milliseconds. When the electrical input is removed, the pawl drops and catches on the next stop disengaging the clutch and mechanically engaging the brake. Two stops are spaced 180 degrees apart. This particular clutch-brake has three important advantages: (1) Only one electrical signal is required which raises the pawl for a sweep; (2) Since the brake is entirely mechanical and is actuated by a fixed stop, timing errors in starting or overrunning in stopping do not accumulate, i.e., the output shaft is always properly registered; (3) At shut down, the clutch is always against a stop which puts the nozzles to the side to facilitate start up without spraying onto the plot.

A programmable industrial process controller generates the electrical pulses at the proper frequency. One pulse every 0.9 sec gives 1.2 in/hr, and one every 0.5 secs gives 2.3 in/hr. The intensity resolution increases from 0.15 in/hr at 1 in/hr intensity to 1.2 in/hr at 5 in/hr for the 0.1 sec standard timer resolution of the controller and the scheme of resting the nozzle after each pass. If multiple passes are permitted without a rest, and the total cycle for the series of passes and rest is 4 sec or more, the resolution is 0.1 in/hr at the higher intensities. Also, the controller can be programmed for a 0.01 sec resolution for finer intensity resolution for intensities up to 3.8 in/hr. The programmable controller permits very precise calibration of rainfall rate and compensation for controller and mechanical tolerances. The controller is programmed so that spray from adjacent troughs does not meet over the plot to avoid collision of drops which might change drop size distribution.

The standard program in the controller allows the operator to select, by switch, an intensity of either 1 1/4, 2 1/2, or 5 in/hr. The intensity, switchable during a run, is uniform under the entire simulator. Duration of the run (1/2 hr, 1 hr, or manually timed) is switch selectable and is timed by the controller. The program is stored permanently in a memory module. Other intensities are available by programming additional inputs, reprogramming existing inputs, or changing time values in designated storage registers in the controller memory.

Variable intensities in time and space can also be programmed in a spare memory module to study moving storms and various storm intensity patterns (e.g., advanced, delayed, uniform). Such programs can be stored indefinitely in the memory module or can be reprogrammed as the need requires. The processor retains its memory contents indefinitely and does not require reprogramming after power is turned off.

Electrical Power

Electricity for the pumps, motors, and controller is supplied by a 45 kw generator driven by a 98 hp gasoline engine with a hospital level silencer to minimize noise. Power, 220 vac-single phase, is fed to a NEMA 3R cabinet enclosing a distribution panel, switches, and the controller. Ground fault interruptors prevent shocks. Switches within the cabinet turn on the controller, and the drive motors and pumps in groups of four.

A remote control panel on a 200 ft cable is connected to the panel with easily removed connectors. Intensity (1 1/4, 2 1/2 or 5 in/hr); duration of run (1/2 hr, 1 hr, or manually timed); and stop, reset, and start controls are available at the remote panel.

A 12-conductor cable with 12 gage wires from the main panel provides 110 vac power and control signals for a 4 trough unit. Near the 4 trough unit, power and control signals are distributed through a subdistribution box to each individual trough. Connectors facilitate easy connecting and disconnecting of cable at erection and teardown of the simulator.

A 7-conductor cable with 12 gage wires brings power from the subdistribution box to the detachable drive box containing the drive motor and clutch-brake. A wiring harness distributes power to the drive motor, the clutch-brake, and the sump pump at the opposite end of the trough.

Structure

The trough is made of 24 gage galvanized sheet steel. Initially, 28 gage steel was considered, and a prototype showed that 28 gage was feasible. However, the 28 gage trough was susceptible to dents and failure if the upper edges are not quite stiff. Consequently, the design is for a 24 gage trough, 15 in wide by 11 in high. The critical upper edge is a right angle bend with 1.5 in of material doubled back.*

Design load was: 25 lb/ft trough and water weight, 25 lb (pump) and 20 lb (drive components) concentrated loads at either ends of the trough, 20 lb/ft wind load, and gravitational forces on a 3:1 slope. Bulkheads, cross braces which hold the nozzle assembly above each deflector, and diagonal braces between the bulkheads provide rigidity and lateral bracing. The trough lid carries no load. Joints are butted and overlapped with a splice. Fasteners are sheet metal screws and spot welds. Total length of the trough not including the detachable drive box is 16 ft 9 1/2 in. Silicone sealant is used to waterproofs joints.

The main support structure supports 4 troughs as a unit independent from other units. The main element in the structure is an inverted U set laterally

---

* Since the steel trough proved excessively heavy, we are currently evaluating a trough with reduced dimensions of 6061-T6 aluminum alloy, 0.032 in thick. Preliminary indications indicate that the aluminum trough will be satisfactory at a considerable weight savings.

across the plot. A support unit is two inverted U's jointed by two-6 in, schedule 10 aluminum pipes. The troughs rest on the pipes. The U's are spaced 10 ft apart upslope.

Vertical less of the U, spaced 13 ft apart laterally across the slope, are joined by a 6 in horizonal aluminum pipe. The entire U is welded except in the middle which separates with the removal of a pin to facilitate handling and transport. Legs of the U are pinned before they are carried to plot to avoid having to walk on the plots during assembly.

The vertical legs telescope over a 2 ft 3 in range. The unit is lowered to 6 ft, the troughs are installed, and electric drills are used at directly opposite corners to raise the unit to 8 ft. Telescoping is by a right angle drive and an acme screw in the leg. The upper part of the leg is 6 in diameter aluminum pipe, and the lower telescoping part is 3 in diameter aluminum pipe. A 2 ft extension can be inserted to raise the simulator an additional 2 ft to reduce the effects of crop canopy.

The two inverted U's for a four-trough unit are joined together by two-6 in diameter pipes, one on each side. Each pipe rests in a saddle where it is tied down with two easy to tighten straps. The joints carry a moment load eliminating the need for any brace wires or braces on slopes up to 20%.

The troughs are tied to the connecting pipes with tool box hasps and catches. One of the connecting pipes is a water supply connected to the trough by a 1/4 turn coupling and a flexible hose.

ESTIMATED CONSTRUCTION COSTS

A simulator of this design is under construction. Costs (as of May 1, 1979) given below are based on 8 troughs, 2 frame units, electrical cable for 8 troughs, and generator, controller, and panel for 32 troughs. Unit cost for components like the trough depends on the number built at a time.

Trough Assembly	Cost/Trough
Basic sheet metal trough (Materials and labor)	$ 550
Drive motor	$ 67
Bearing	$ 4
Clutch-brake	$ 106
Sprockets and chain	$ 13
Miscellaneous brackets, shafts, and connecting link	$ 10
Pump	$ 121
Float valve	$ 56
Swivel joints (5 required @ $10.27 each)	$ 51
Nozzles and flow straighteners (5 required @ $3.28 each)	$ 16
Valves, pipe, and pressure gage	$ 82
Wiring, conduit, and receptacles	$ 15
Final assembly labor	$ 80

	Total	$1,171

Frame (one unit required/4 troughs)	Cost/Unit
Material and labor	$1,250

Electrical equipment	Costs
Generator, 45 kw (1 required/32 troughs)	$5,002
Distribution Panel and Switches (1 required/32 troughs)	$5,730
Wiring cable, subpanel, and wiring harness for 4 troughs (cost/4 trough unit)	$ 895
Process controller	$4,516

Transport	Cost
Trailer	$4,978

Total	Cost
32 troughs, 8 frame units	$66,000

WEIGHT

Each trough, completely assembled without the detachable drive box, weighs approximately 175 lb.* The drive box weighs approximately 25 lb. while half of a U frame weighs about 50 lb. The electrical cable from the distribution panel to a 4 trough unit is 166 lb for a 200 ft cable. The distribution panel and the generator are mounted on the transport trailer.

SIMULATOR PREFORMANCE

The obvious proof of this design will be satisfactory performance of a constructed rainfall simulator. Two prototype troughs are operating. Control of intensity is excellent and the controller works as intended. The design goal of cycle times of 1 sec and less was attained. Hydraulic performance of the troughs also is entirely satisfactory. Weight of the troughs and electrical cables is excessive. The design is being refined to remedy these problems, and progress indicates that the simulator will be usable as a field simulator. It has already proven adequate for laboratory studies. Since none of the framework has been constructed, we cannot comment on the adequacy of its design.

* This will be reduced to approximately 100 lb if the aluminum trough proves satisfactory.

REFERENCES

1. Barnett, A. P. and A. E. Dooley, 1972. Erosion potential of natural and simulated rainfall compared. Trans. Amer. Soc. of Agric. Engr. 15(6):1112-1114.

2. Bubenzer, G. D. and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans. Amer. Soc. of Agric. Engr. 8(1):73, 75.

3. Grierson, I. T. and J. M. Oades. 1977. A rainfall simulator for field studies of runoff and soil erosion. Journal Agric. Engr. Research 22:37-44.

4. Hermsmeier, L. F., L. D. Meyer, A. P. Barnett, and R. A. Young. 1963. Construction and operation of a 16-unit rainulator. ARS 41-62, USDA-Science and Education Administration. 136 pp.

5. McGregor, K. C. and C. K. Mutchler. 1977. Status of the R-Factor in Northern Mississippi. Soil Erosion: Prediction and Control. Special Publication No. 21 Soil Conservation Soc. of Amer. Ankeny, Iowa. pp 135-142.

6. Meyer, L. D. 1958. An investigation of methods of simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles. Special Report No. 81. USDA-Science and Education Administration. 43 pp.

7. Meyer, L. D. and W. C. Harmon. 1977. Rainfall simulator for evaluating erosion rates and sediment sizes from row sideslopes. Paper No. 77-2025, Amer. Soc. of Agric. Engr., St. Joseph, Michigan.

8. Meyer, L. D. and D. L. McCune. 1958. Rainfall simulator for runoff plots. Trans. Amer. Soc. of Agric. Engr. 39(10):644-648.

9. Swanson, N. P. 1965. Rotating-boom rainfall simulator. Trans. Amer. Soc. of Agric. Engr. 8(1):70-71.

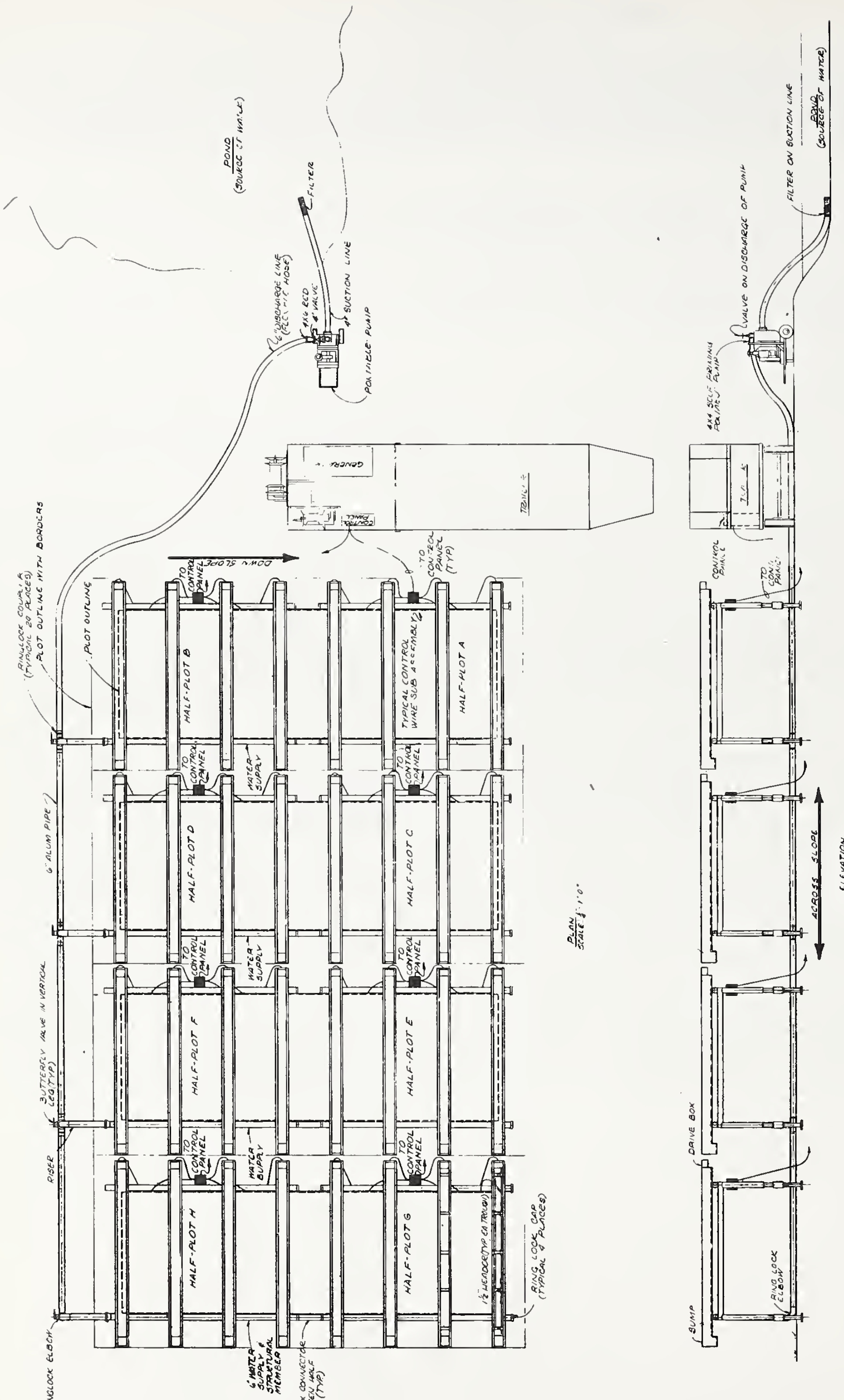
10. Young, R. A. and R. E. Burwell. 1972. Prediction of runoff and erosion from natural rainfall using a rainfall simulator. Soil Sci. Soc. Amer. Proc. 36(5):827-830.

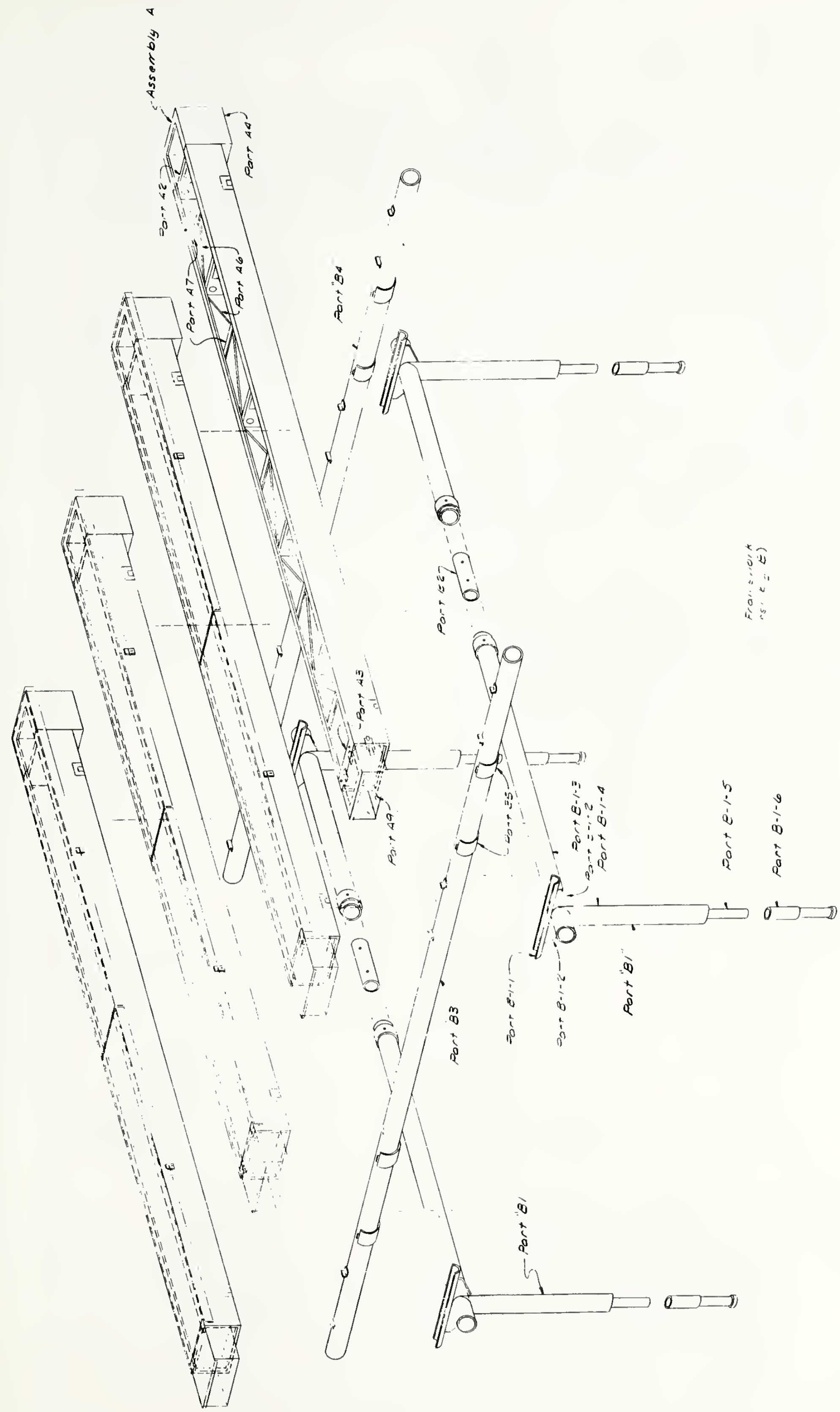
APPENDIX I - DRAWINGS

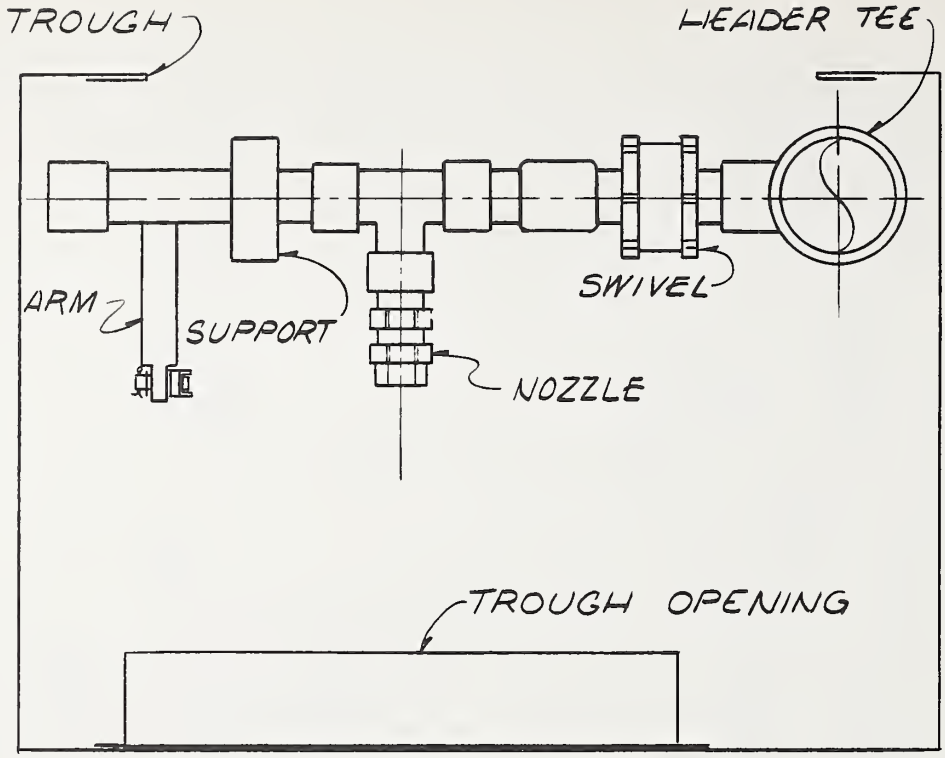
The following drawings illustrate general details of the simulator. More detail drawings and specifications are available on request from G. R. Foster, USDA-SEA, Agricultural Engineering Dept., Purdue University, West Lafayette, IN 47907.

Drawings:

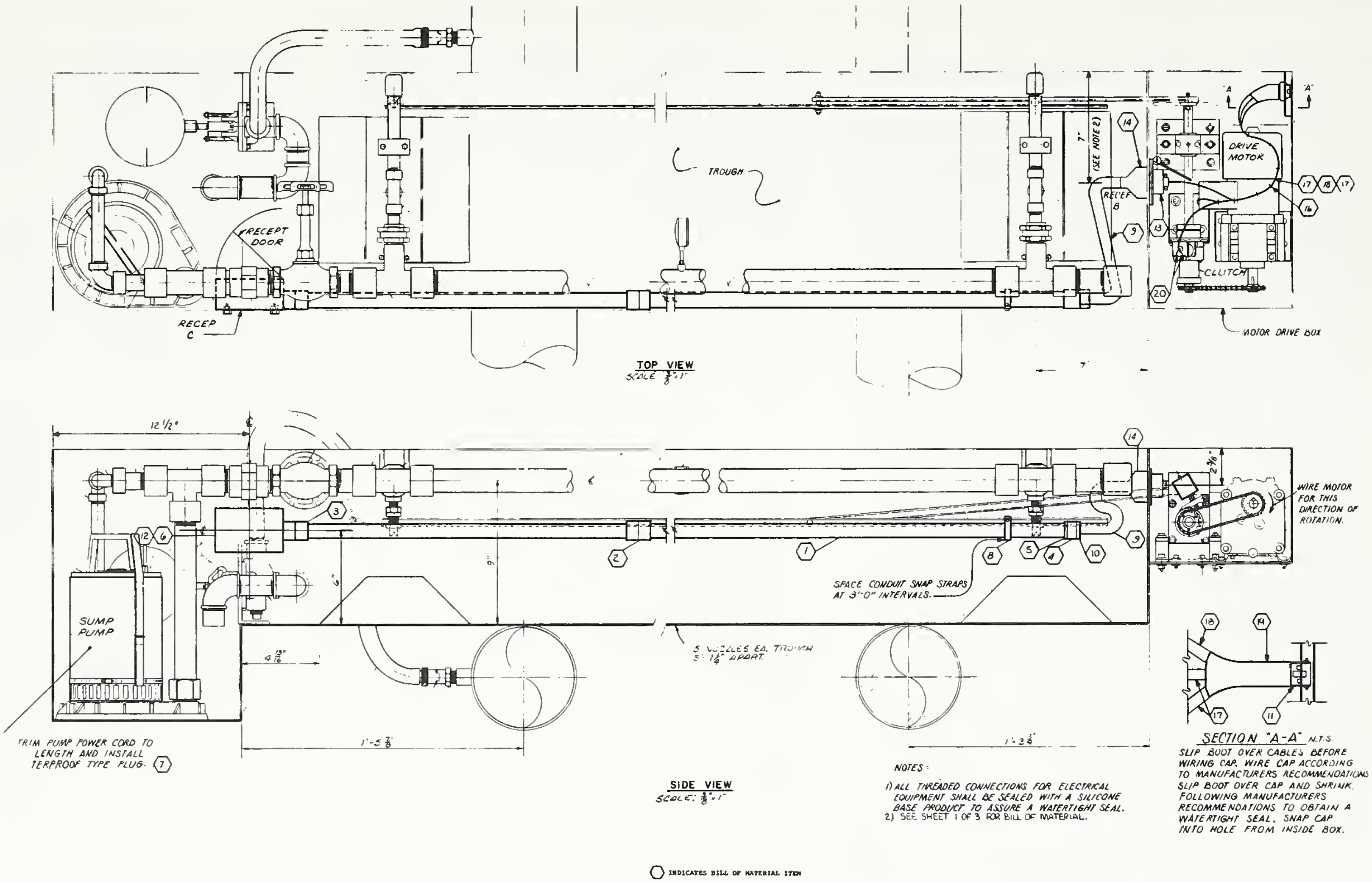
- Plan of troughs, electrical, trailer, pump, and pond
- Exploded view of troughs and frame
- Cross section of trough
- Top view of trough
- Side view of trough


POND (SOURCE OF WATER)
FILTER
SUCTION LINE
PORTABLE PUMP
CONTROL PANEL
DOWN SLOPE
TO CONTROL PANEL
TO CONTROL PANEL (TYP)
PLOT OUTLINE
PLOT OUTLINE WITH BORDERS
HALF-PLOT A
HALF-PLOT B
HALF-PLOT C
HALF-PLOT D
HALF-PLOT E
HALF-PLOT F
HALF-PLOT G
HALF-PLOT H
TYPICAL CONTROL WIRE SUB ASSEMBLY
WATER SUPPLY
6" ALUM PIPE
BUTTERFLY VALVE IN VERTICAL LEG (TYP)
RISER
RINGLOCK ELBOW
6" WATER SUPPLY & STRUCTURAL MEMBER
RING LOCK CAP (TYPICAL 4 PLACES)
PLAN
ELEVATION
ACROSS SLOPE
DRIVE BOX
SUMP
RING LOCK ELBOW
VALVE ON DISCHARGE OF PUMP
FILTER ON SUCTION LINE


Assembly A
Part A4
Part A2
Part A7
Part A6
Part B4
Part A3
Part A9
Part B-1-3
Part B-1-4
Part B-1-5
Part B-1-6
Part B1
Part B-1-1
Part B3
Part B1


TROUGH
HEADER TEE
ARM
SUPPORT
SWIVEL
NOZZLE
TROUGH OPENING

SECTION


TROUGH
DRIVE MOTOR
CLUTCH
RELIEF B
RECEPT DOOR
RECEP C
MOTOR DRIVE BOX
7" (SEE NOTE 2)
TOP VIEW
SCALE 3/8"=1'
12 1/2"
SUMP PUMP
TRIM PUMP POWER CORD TO LENGTH AND INSTALL TERPROOF TYPE PLUG. 7
SPACE CONDUIT SNAP STRAPS AT 3'-0" INTERVALS.
5 NOZZLES EA. TROUGH 3' 1 1/4" APART.
WIRE MOTOR FOR THIS DIRECTION OF ROTATION.
1'-5 7/8"
1'-3 3/4"
4 13/16"
SIDE VIEW
SCALE: 3/8"=1'
NOTES:
1) ALL THREADED CONNECTIONS FOR ELECTRICAL EQUIPMENT SHALL BE SEALED WITH A SILICONE BASE PRODUCT TO ASSURE A WATERTIGHT SEAL.
2) SEE SHEET 1 OF 3 FOR BILL OF MATERIAL.
SECTION "A-A" N.T.S.
SLIP BOOT OVER CABLES BEFORE WIRING CAP. WIRE CAP ACCORDING TO MANUFACTURERS RECOMMENDATIONS SLIP BOOT OVER CAP AND SHRINK. FOLLOWING MANUFACTURERS RECOMMENDATIONS TO OBTAIN A WATERTIGHT SEAL. SNAP CAP INTO HOLE FROM INSIDE BOX.
INDICATES BILL OF MATERIAL ITEM

RAINFALL SIMULATION AS A RESEARCH TOOL[1/]

K. G. Renard, SEA Research Leader[2/]

As I approached the assignment of incorporating the comments of W. C. Moldenhauer and C. R. Amerman (who were on the original program but were unable to attend) with mine, I became apprehensive about how to accomplish such as assignment. Therefore, I have selected a few problems they point out, and have added a few of my own. Earl Neff, in his opening remarks, discussed the advantages and disadvantages of rainfall simulators. It appears that most of the participants favor the use of rainfall simulators. As Mech (1) pointed out, "It is much more popular to accentuate the positive. To point out the weakness or shortcomings of a tool so highly regarded and so widely accepted is not without real peril."

Among the factors which are difficult to emulate with a simulator, but which affect the simulation are wind, temperature, humidity, vegetative influences, soil surface and moisture, and frozen soil and snowmelt. Amerman states in his write-up (2), "To be on the safe side, one may simply state that the 'best' sprinkling infiltrometer is the one that most nearly emulates natural precipitation--drop size, kinetic energy, average intensity or intensity pattern, duration, temperature, etc." He goes on to point out that ". . . one seldom sees temperature discussed, and hydraulic conductivity is influenced by temperature. I suspect that for many field infiltrometer tests, neither water nor soil is at temperatures representative of storm conditions." Our experience in Tucson is an example of such an operating procedure. Most of our rainfall simulation work has been conducted during the fall, winter, or spring periods, yet almost all of the runoff results from summer thunderstorms where the cold precipitation (e.g., 50^{0} F) strikes soil surfaces with temperatures well over 100^{0} F. How important is this? I could find nothing quantitative in the literature, but I suspect it might be significant. By the same reasoning, errors introduced by this oversight might be much less than those generated by using point values to infer the spatial heterogeneity of the vegetation and soil within relatively short distances.

Most infiltrometers currently in use have not measured the effect of surface head on infiltration. We all recognize that the problem of infiltration is a two-phase flow problem (water and air). Dixon (3) showed that a parameter, which he defined as effective surface head (the difference between the surface water hydrostatic pressure and the soil air back pressure), markedly

---

1/ Contribution of the Soil, Water and Air Sciences Research USDA-SEA-AR-Western Region.

2/ Southwest Rangeland Watershed Research Center, USDA-SEA-AR, 442 East 7th Street, Tucson AZ 85705.

changed infiltration. He designed an infiltrometer to quantify this effect (closed top infiltrometer; Dixon (4)), and has demonstrated that infiltration rate can be changed by an order of magnitude by controlling the effective surface head. Little use of this equipment is being made by other investigators, and the idea of this pressure difference is not being actively pursued.

For some time, I have been concerned about the variation in the distribution of raindrop sizes in the wide variety of climatic provinces with which we conduct our research. Variation occurs seasonally as well as within individual storms, but most rainfall simulators are designed to reproduce the kinetic energy of some storm which may or may not be representative of the region. Moldenhauer points out other problems of simulation in his handout (5):

> Simulated rain was compared to natural rain by Meyer (6). Sloneker and Moldenhauer (7) and Sloneker et al. (8), studied the effect of intermittency on soil from rain simulated by oscillating nozzles and found problems when a wide range of intensities are simulated because of recovery of soil suction during the off time. Young and Burwell (9) found, however, very comparable erosion from comparable simulated and natural storms.

A logical extension of this concept is to ask, "How much do we know about the characteristics of drop sizes in different parts of the country?" I suspect the answer is not enough, even though we had one panel address the problem. For example, the "R" term of the Universal Soil Loss Equation (USLE) is based on limited rainfall information despite limited information which has subsequently verified the Laws and Parsons (10) data.

McGregor and Mutchler (11) showed that for storms in Mississippi, the kinetic energy/rainfall intensity relationship was quite similar to the data for Washington, DC. Can we be sure that serendipity has not entered into this relationship? The scatter of data (Fig. 1) is appreciable, and may partly explain the problem encountered when efforts are made to use the USLE on individual storms. Might not experiments be warranted to define this variability across the climatic extremes of the country, and might not the envelope curves explain the wide differences in observed erosion on individual storms? Can we even design simulators to duplicate such data variability, or can we use stochastic techniques with mathematical modeling to depict such phenomenon?

Wischmeier and Smith (12) state, "The energy of a rainstorm is a function of the amount of rain and of all the storm's component intensities. Median raindrop size increases with rain intensity, and terminal velocities of free-falling waterdrops increase with increased drop size. Since the energy of a given mass in motion is proportional to the velocity-squared, rainfall energy is directly related to rain intensity." Although it is difficult to question the statement, it seems intuitive that different meteorologic conditions in different parts of the country may cause the median drop size/rain intensity relationship to be more complex than postulated by Wischmeier and Smith.

Drop sizes are customarily measured using the ozalid paper, flour pan, or high-speed camer method. Recent information regarding a transducer being

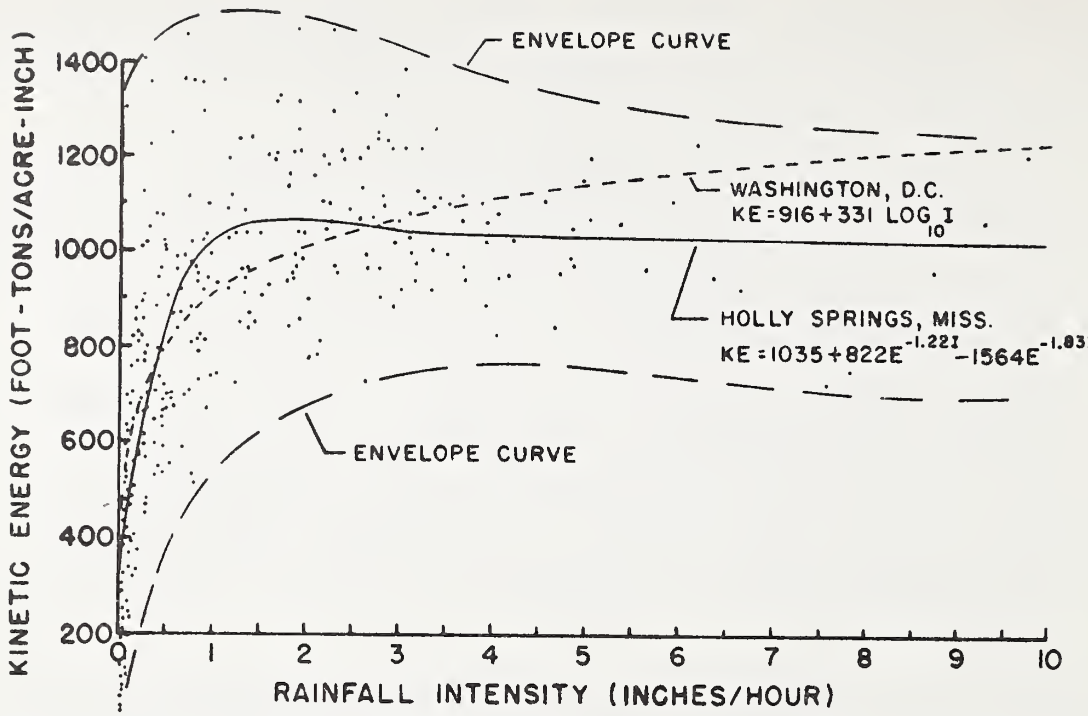


Figure 1.--Relationship of kinetic energy and rainfall intensity computed from 315 raindrop samples collected at Holly Springs, Mississippi, compared with that derived from raindrop samples collected at Washington, D.C., and extrapolated above intensities of 4 inches per hour (10.2 cm/hr) (adapted from Mcgregor and Mutchler, 1976).

developed by the Illinois State Water Survey illustrates one approach at improving such measurements.

Richard G. Semonin, Atmospheric Sciences Section of the Water Survey, has been working with the schematic illustrated in Figure 2, and has developed the equipment to the point of preparing a publication on the design, calibration, and some observations on the operation of the unit. Calibration requires using drops falling in a 13-meter chamber. The unit can be assembled (exclusive of the recorder) for under $1,000 - a cost which seems reasonable.

A nationwide network of these transducers could produce the data to develop relationships between storm intensity and raindrop size (assuming a unique relation does exist), and lead to criteria for better nozzle designs for use in construction of rainfall simulators. Another opportunity might be to include a series of the nozzles reported by Don Meyer (13) in a random pattern over a large plot. With better nozzles, it should be possible to simulate a range of storm intensities using the drop sizes typical to the region in question. Furthermore, information on drop sizes in different areas of the country might afford the opportunity to modify the "R" values for use in the USLE and eliminate some problems like that of restricting the upper limit of the annual units of R in certain portions of the country.

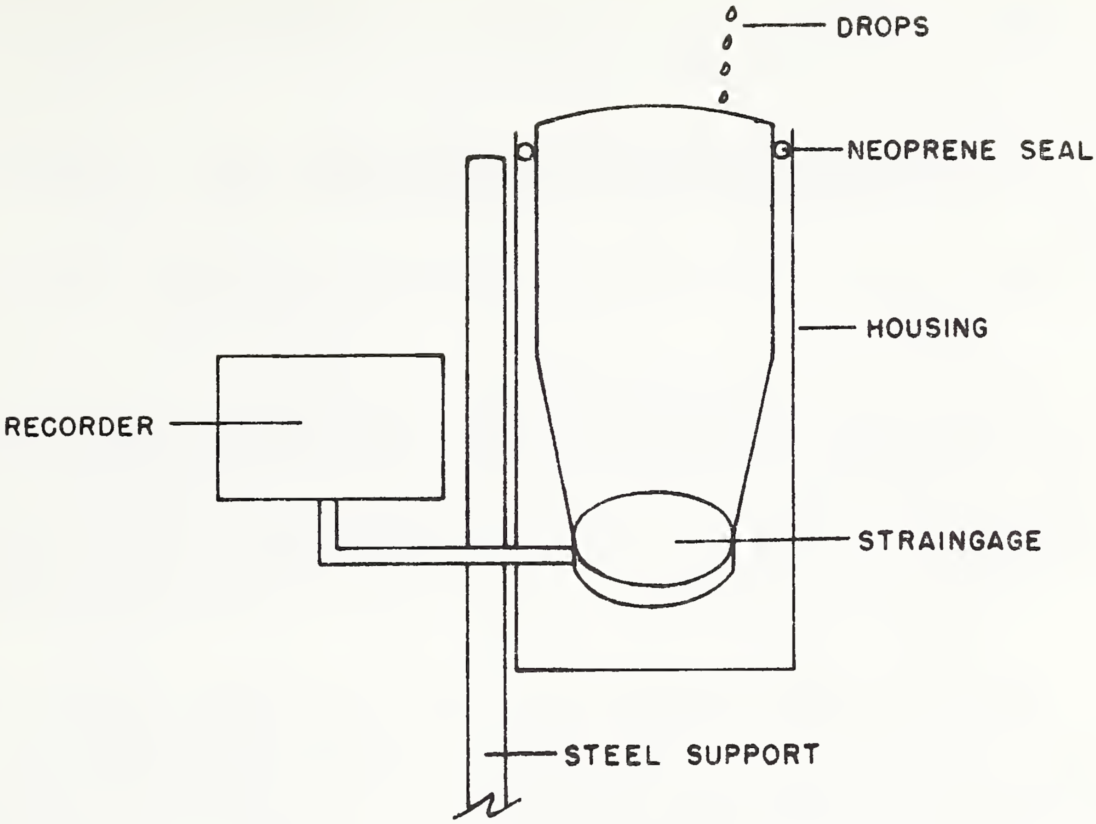


Figure 2.--Raindrop-size transducer schematic.

Rainfall simulators are valuable for infiltration and erosion research, and are the only way to answer many of the questions being asked. At the same time, we need more research to improve rainfall simulators; to see if the many simulators being used are providing compatable information; and to see if this information adequately mimics the conditions encountered in the problem area.

LITERATURE CITED

(1) Mech, S. J.
1965. Limitations of simulated rainfall as a research tool. Trans. ASAE 8:66-67.

(2) Amerman, C. R.
1979. Rainfall simulation as a research tool in infiltration. Proc. of Rainfall Simulator Workshop.

(3) Dixon, Robert M.
1975. Infiltration control through soil surface management. Proc. Symp. on Watershed Management, Irrigation and Drainage Division, ASCE, Logan, Utah, p. 543-567.

(4) Dixon, Robert M.
1975. Design and use of closed-top infiltrometers. Soil Sci. Soc. of Am. Proc. 39:755-763.

(5) Moldenhauer, W. C.
1979. Rainfall simulation as a research tool. Proc of Rainfall Simulator Workshop.

(6) Meyer, L. D.
1965. Simulation of rainfall for soil erosion research. Trans. ASAE 8:63-65.

(7) Sloneker, L. L., and Moldenhauer, W. C.
1974. Effect of varying the on-off time of rainfall simulator nozzles on surface sealing and intake rate. Soil Sci. Soc. Amer. Proc. 38: 157-158.

(8) Sloneker, L. L., Olson, T. C., and Moldenhauer, W. C.
1976. Effect of pore water pressure on sand splash. Soil Sci. Soc. Amer. Jour. 40:948-951.

(9) Young, R. A., and Burwell, R. E.
1972. Prediction of runoff and erosion from natural rainfall using a rainfall simulator. Soil Sci. Soc. Am. Proc. 36:827-830.

(10) Laws, J. O., and Parsons, D. A.
1943. The relation of raindrop size to intensity. Trans. Am. Geophys. Union 24:452-459.

(11) McGregor, K. C., and Mutchler, C. K.
1976. Status of the R factor in northern Mississippi. In Soil Eroson: Prediction and Control. SCSA Special Publication No. 21, p. 133-142.

(12) Wischmeier, W. H., and Smith, D. D.
1978. Predicting rainfall erosion losses - A guide to conservation planning, USDA Agricultural Handbook No. 537, 58 pg.

(13) Meyer, D.
1979. Methods for attaining desired rainfall characteristics in rainfall simulators. Proc. of Rainfall Simulator Workshop.

INFERRING CURVE NUMBERS FROM SIMULATOR DATA [1/]

By Richard H. Hawkins [2/]

ABSTRACT

The hydrologic data produced by rainfall simulator devices may be used to calculate observed runoff curve numbers. The data may or may not be consistent with 1) the functional relationships specified by the curve number runoff equation, and 2) handbook curve number values. Both calculation algorithms and measurement methods affect the outcome of such calculations, and thus the validity of the results. Some suggestions for data analysis and measurement strategy are given.

INTRODUCTION

It is inevitable that rainfall simulation should lead to the temptations of curve numbers. Simulation is carried out because of the inherent control and relative convenience in investigating land hydrology processes. Curve numbers are land condition coefficients used in an institutionalized rainfall-runoff equation of a very specific form, i.e.,

$$Q = (P-0.2S)^2/(P+0.8S) \qquad P \geq 0.2S \qquad [1]$$

$$Q = 0 \qquad P \leq 0.2S$$

$$\text{where, } S = (1000/CN) - 10 \qquad [2]$$

CN being the curve number, Q the runoff depth at rainfall depth P, and S an index of potential site moisture storage and related to CN as shown by [2]. The classical plot of Q on P for families of CN is shown in Figure 1, taken from the standard reference document on the topic, the SCS National Engineering Handbook, Section 4, "Hydrology," or "NEH-4" (6).

As used in practice as a point of departure to generate hydrographs, Q is differenced for P, progressing throughout a design rainstorm. Q is then used as Q(t), and P as P(t), but S is held constant throughout, invariable for each land condition and initial soil moisture. Although no measure of rainfall intensity is included, it can be easily shown by differentiation of [1] that

---

1/ Paper given at USDA Rainfall Simulator Workshop, Tucson, Arizona, March 7-9, 1979.

2/ Associate Professor, Department of Forestry and Outdoor Recreation and Civil and Environmental Engineering, Utah State University, Logan, Utah 84322.

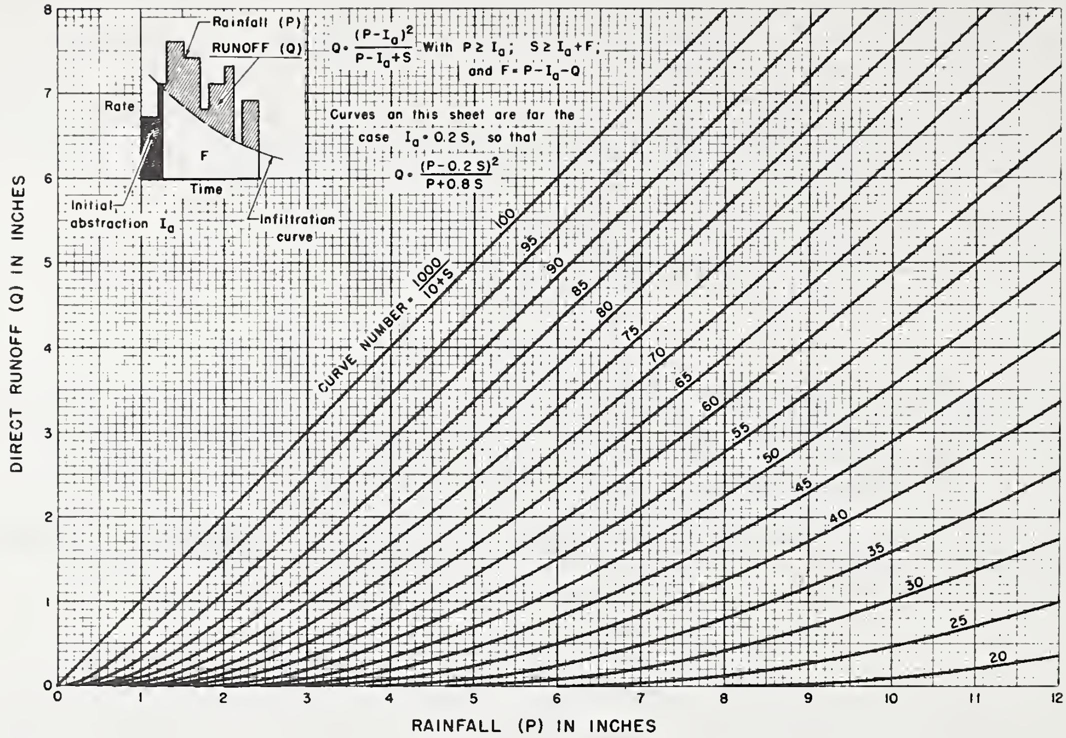


Figure 1. Curve number rainfall-runoff relationships. Source: NEH-4(6).

$$f(t) = i(t) \left(\frac{S}{P(t) + 0.8S}\right)^2 \qquad P(t) \geq 0.2S \qquad [3]$$

where f(t) and i(t) are momentary infiltration and rainfall intensity, respectively, and i(t) is dP(t)/dt. Graphical representation of [3] is given in Figure 2.

It should be noted that: 1) Eq. 3 is meaningful only for $P(t) \geq 0.2S$; 2) the function resembles our preconceived notions of infiltration with time; and 3) as $t \to \infty$, $f(t) \to 0$, or there is no residual constant characteristic rate analogous to f_c in Horton's equation. Thus, given a constant rainfall intensity (as often attempted or assumed with rainfall simulation), f(t) becomes only a function of S (or CN). Figure 3 shows a family of infiltration curves from Eq. [3] for various values of CN for the example intensity of 1.00 in/hr.

It should be easily seen that any observed point of $Q \leq P$ in Figure 1, or $f/i \leq 1$ in Figure 2 defines an observed curve number. Successive points define the progress of CN with rainfall or time, respectively, and constant observed curve numbers will affirm the validity of Equations 1 and 3.

Calculations of S, and thus CN, may be made from data through either [1] or [3]. All quantities except S are usually measured in simulator trials: rainfall and runoff totals P and Q, and rates i and f with time t. If the

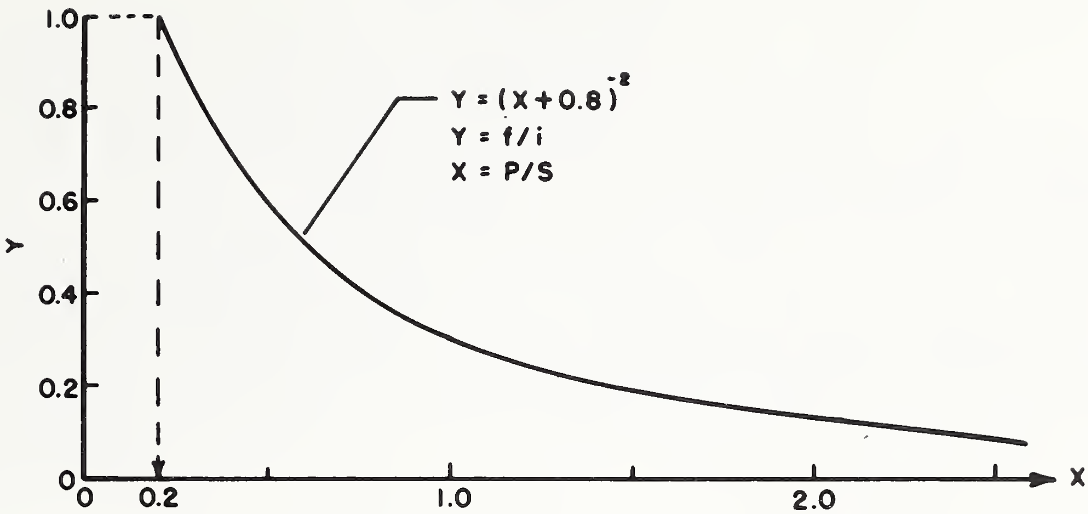


Figure 2. Dimensionless expression of infiltration inferred by curve number equation

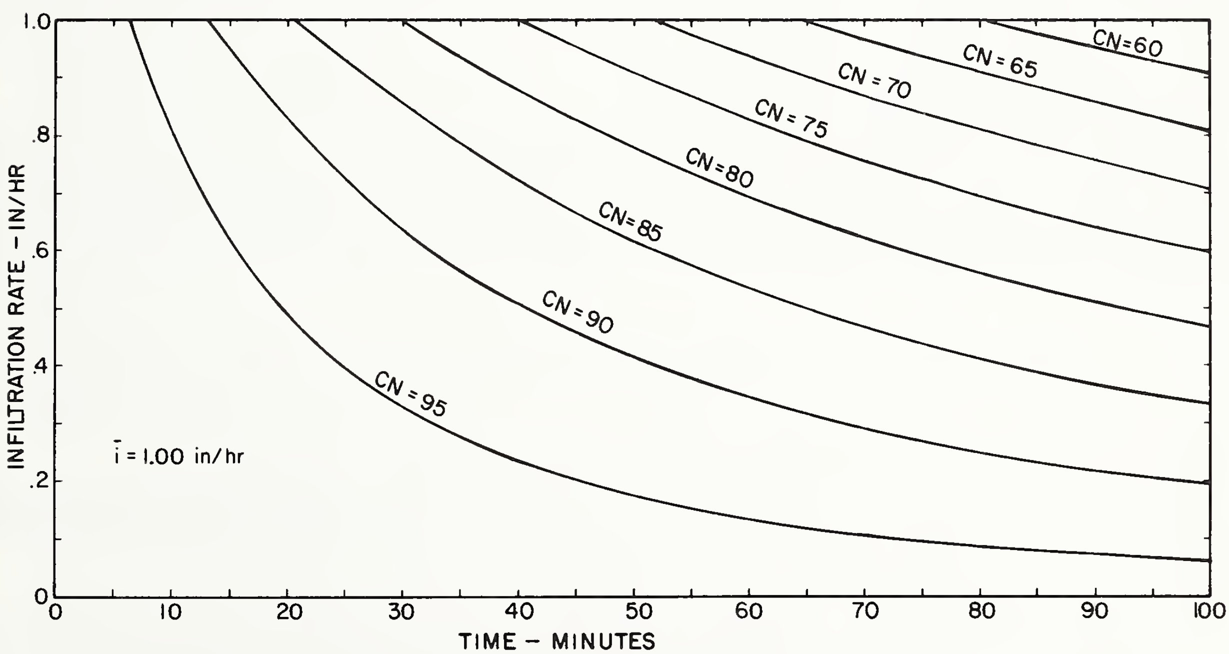


Figure 3. Family of infiltration curves for uniform storm of 1.00 in/hr.

functional structure [1] and [3] conforms to observed reality then S should calculate as a constant, and CN should likewise be fixed. The means of doing this, and the problems that arise are the topic of this paper.

TECHNIQUES

A variety of data analysis opportunities may be used, varying with the analyst's degree of belief in the curve number method, and dealing with either 1) rainfall-runoff, or 2) intensity and infiltration.

1. Total Rainfall and Runoff Only

Equation 1 is solved directly via the quadratic formula for S, and thus for CN via [2]. The solution for S is:

$$S = 5(P + 2Q - \sqrt{4Q^2 + 5PQ}) \qquad [4]$$

Only the final total rainfall and runoff are used.

2. Progressive Rainfall and Runoff

A least squares solution for <u>all</u> the available P and Q throughout the trial is used, fixing S by an iteration procedure, by minimizing ^{2} where

$$\Sigma\Delta^2 = \Sigma[Q(t) - \hat{Q}(t)]^2 \qquad [5]$$

where $\hat{Q}(t)$ is calculated from [1].

3. Final infiltration rate

The infiltration and rainfall rates, and the total rainfall depth, at the end of the event are simply substituted into [3], and S determined directly. The solution is:

$$S = P \ \sqrt{Z}/(1 - 0.8 \ \sqrt{Z}) \qquad [6]$$

where $Z = f/i \leq 1$, and $P \geq 0.2S$

4. Progressive infiltration fitting

The infiltration function (Eq. 3) is fit by varying S to all the observed data, and the squared differences minimized, as per

$$\Sigma\Delta^2 = \Sigma(f(t) - \hat{f}(t))^2 \qquad [7]$$

where, f(t) is the observed infiltration rate at time t, and $\hat{f}(t)$ is calculated from Equation 3.

For data with no error, and for a system which matches the CN equations, the above methods should provide identical estimates of S or CN. Also, there

exist variations in the above themes. For example, the losses $F + I_a$ could be fit to P in method 2, presumably leading to identical estimations of S.

DATA AND RESULTS

Simulator data from three sources was assembled to illustrate the above methods and to point out problems. These data are as follows:

Arizona

Rainfall simulation at 1.62 inches per hour for 30 minutes with a "USGS" simulator as described by Lusby and Toy (1). The soil is deep, well drained, of medium texture, and of the Laveen series (Hydrologic Soil Group B) formed on calcareous alluvium. There was about a 25% cover density of herbs, grasses, and some litter. The plot was 72.6 feet by 30 feet, on about a 2% slope, located tributary to Walnut Gulch, near Tombstone, Arizona, and locally identified as Montijo Flats. The run was made on March 2, 1978, and the data was supplied to the writer by Dr. L. J. Lane of the USDA-SEA, Southwest Watershed Research Center.

Georgia

Rainfall simulation of 6.73 in/hr for 140 minutes on Alapaha Loamy Sand (Hydrologic Soil Group D) with 90% weed cover. A modified "Purdue" infiltrometer was used. The plot was 3.81 feet square on about 1% slope located near Tifton, Georgia. The data is the first set encountered in Rawls, Yates and Asmussen (5), their identification code 01011D, and run on October 31, 1969.

Utah

Two similar Utah sites were used. Both were on a Mancos shale residual soil in the Price Basin in east central Utah. The soils are shallow, fine textured, and salty, and although unsurveyed, were assumed to be in Hydrologic Soil Group D. Plots were 5 feet long by 1 foot wide. Both runs were at variable intensities with a Rocky Mountain infiltrometer in association with other studies (3, 4).

The first averaged 1.77 in/hr for 58 minutes, on a 9% slope with 95% bare ground. The location is known as the "County Line" site, just off U. S. highway 6 and 50 in Emery County. The run was made on June 28, 1975.

The second averaged 3.86 in/hr for 100 minutes on a 5.4% slope with 46% grass and litter cover. The site, in Carbon County, is designated as "Wattis Road." The data was taken by the writer personally on August 29, 1975.

The Arizona data contained time-lag or routing effects, and thus did not represent pure coordinated rainfall-rainfall excess. It was "deconvoluted" by proportioning on rainfall volumes and maximum total runoff, an approximate procedure felt to introduce only small errors.

The data was analyzed by the four methods described above. All except the Arizona data was treated as a series of sequentially larger storms to gain an appreciation for the effects of run duration. The least squares

studies were carried out by individual "hand" iterations on a mini-computer. Results of this curve fitting exercise are summarized in Table 1, and plots for the fits are given in Figures 4 through 7.

DISCUSSION

Three general questions erupt from the results: 1) The calculation method, 2) effect of time duration of applied rainfall in the calculation, and 3) practical CN assignments for the sites for the events sampled.

Calculation Method

The intensity-infiltration least square method (#4) uses noisy inputs and produces poor fitting outputs. The consistent appearance of $r^2 < 0$, indicating a model standard error greater than the original standard deviation, arises from force fitting Equation 3 to data inconsistent with its structure. Specifically, all data exhibits a residual infiltration rate, while Equation 3 demands that this approach zero. Reconciliation is beyond the powers of statistics. The calculation is also the most complex of the four studied.

The single term intensity-infiltration method (#3) suffers from the same fault, plus it responds to chance elements of a single measurement. Note with the Utah (County Line) data that the 38-minute observation is abnormal; the CN calculated is accordingly affected.

The single term rainfall and runoff method (#1) is simple, but may be influenced by the assumed end-of-run point; i.e., the duration of the run. Note with the Georgia data that 30-minute, 60-minute, and 140-minute data points produce CNs of 82, 74, and 60, respectively. Such variety should be unsettling and intolerable to informed users.

The remaining technique, the least squares analysis of rainfall and runoff still exhibits inconsistency, but is the least offensive. Impressive r^2 values are produced, and the variety with rain duration is lessened, although still present.

Run Duration

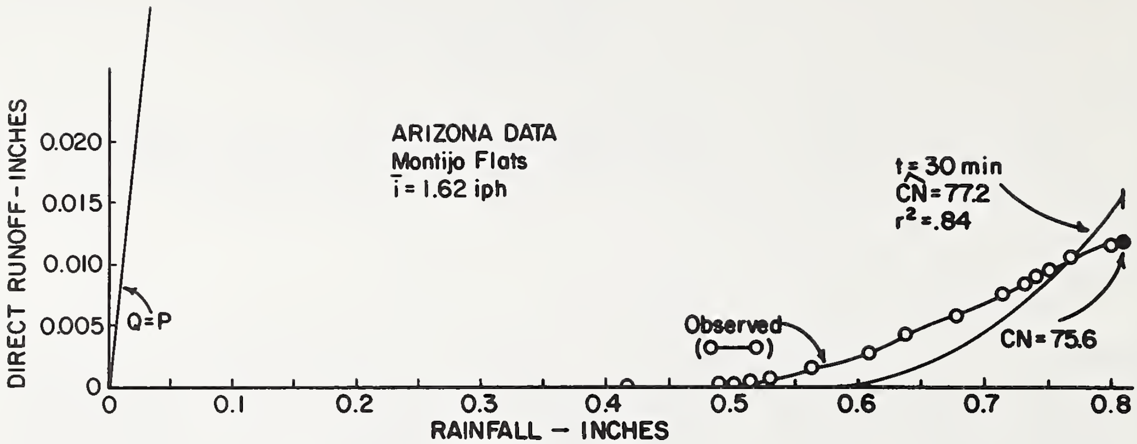
There appears to be no standard time duration to operate simulator-sampling events. As is evident from Table 1 and Figures 4-7, if curve numbers are to be extracted from the data, the duration does make a difference. The effect is detected in the Utah and Georgia data by supposing that the run had been terminated at some interim point. Thus, for example, the Georgia data is a 30-minute run, a 60-minute run, and a 140-minute run, each to be analyzed separately.

To the extent that the rainfall-runoff data intersects and crosses the constant CN lines in Figure 1, the experienced CN becomes smaller with increasing storm size, a phenomenon previously reported (2). Similarly, the experienced near horizontal dance of infiltration rate with time dictates falling CNs with increasing P. Thus the larger the sampling event the smaller

Table 1. General results summary

Data set	Method and input data			
	#1 P,Q	#2 P(t),Q(t)	#3 i,f,P	#4 i(t),f(t),P(t)
<u>Arizona</u>				
$\bar{i}$ = 1.62 iph (Montijo Flats)				
t = 30 minutes	75.6	77.2(.84)	73.2	77.8(-11.5)
<u>Georgia</u>				
$\bar{i}$ = 6.73 iph (Alapaha Loamy Sand)				
t = 30 minutes	82.7	84.9(.97)	72.6	85.5(-2.5)
t = 60 minutes	74.4	79.2(.96)	58.8	80.2(-6.1)
t = 140 minutes	59.9	66.7(.95)	36.2	70.4(-12.8)
<u>Utah</u>				
$\bar{i}$ = 3.86 iph (Wattis Road Site)				
t = 30 minutes	91.8	93.0(.98)	80.5	93.6(.26)
t = 60 minutes	87.7	90.3(.97)	70.3	93.0(-.18)
t = 150 minutes	85.0	87.7(.98)	64.7	92.5(-.30)
i = 1.77 iph (County Line Site)				
t = 28 minutes	95.7	96.3(.99)	90.7	96.0(.69)
t = 58 minutes	95.2	95.6(.99)	92.4	92.1(.77)

Notes: Table entries are calculated runoff numbers. Figure in parentheses is r^2 where appropriate. Unsubscripted P, Q, i, or f indicates final or total value at time indicated.



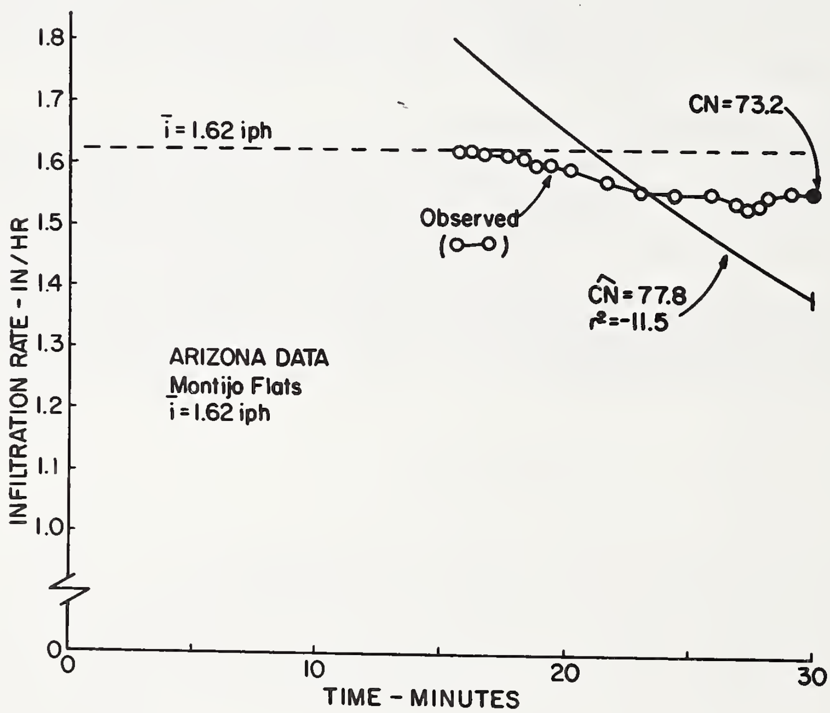


Figure 4. Rainfall, runoff, infiltration, and fitted expression of curve numbers for Arizona Montijo Flats data.

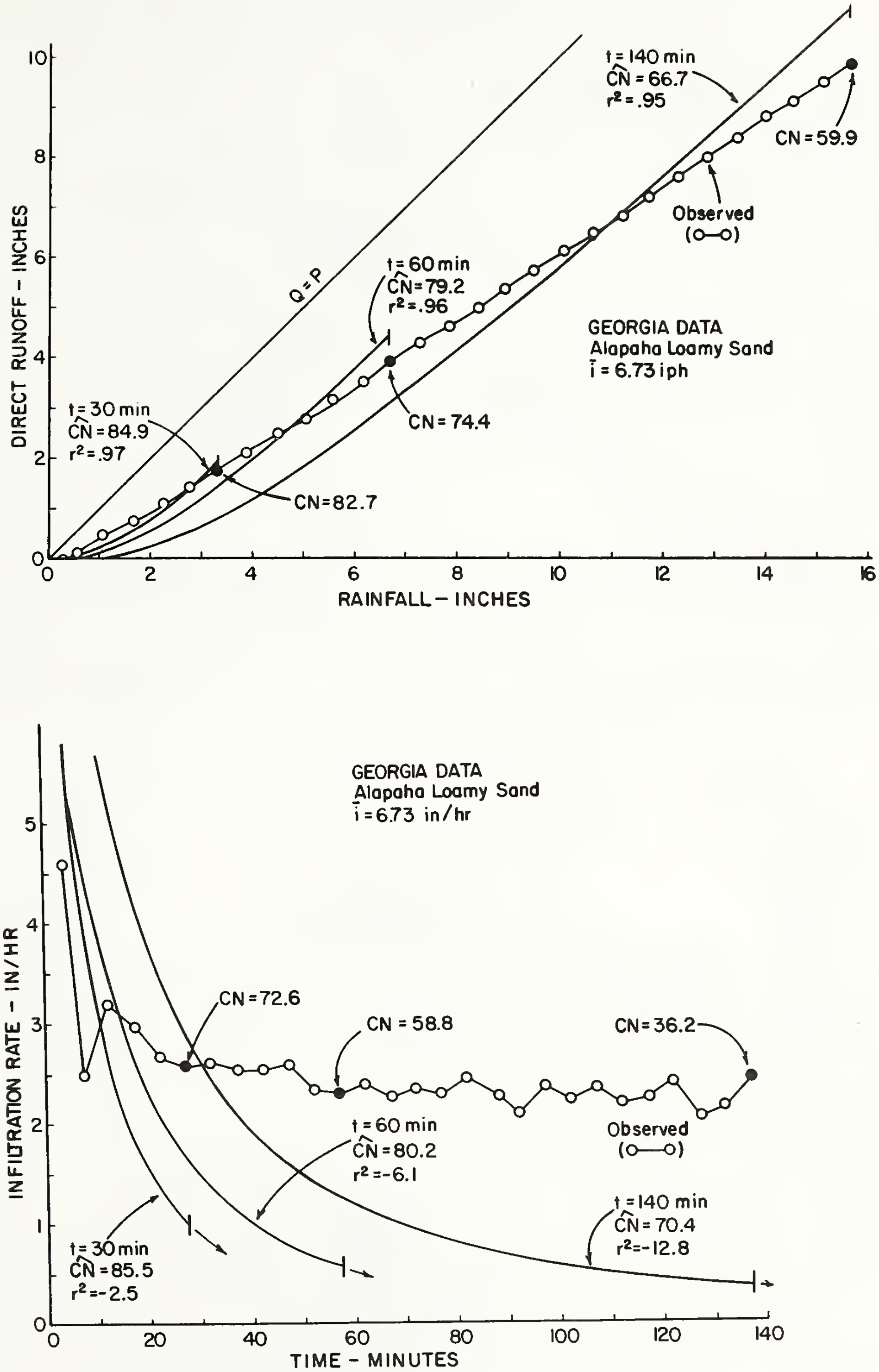


Figure 5. Rainfall, runoff, infiltration, and fitted expression of curve numbers for Georgia data.

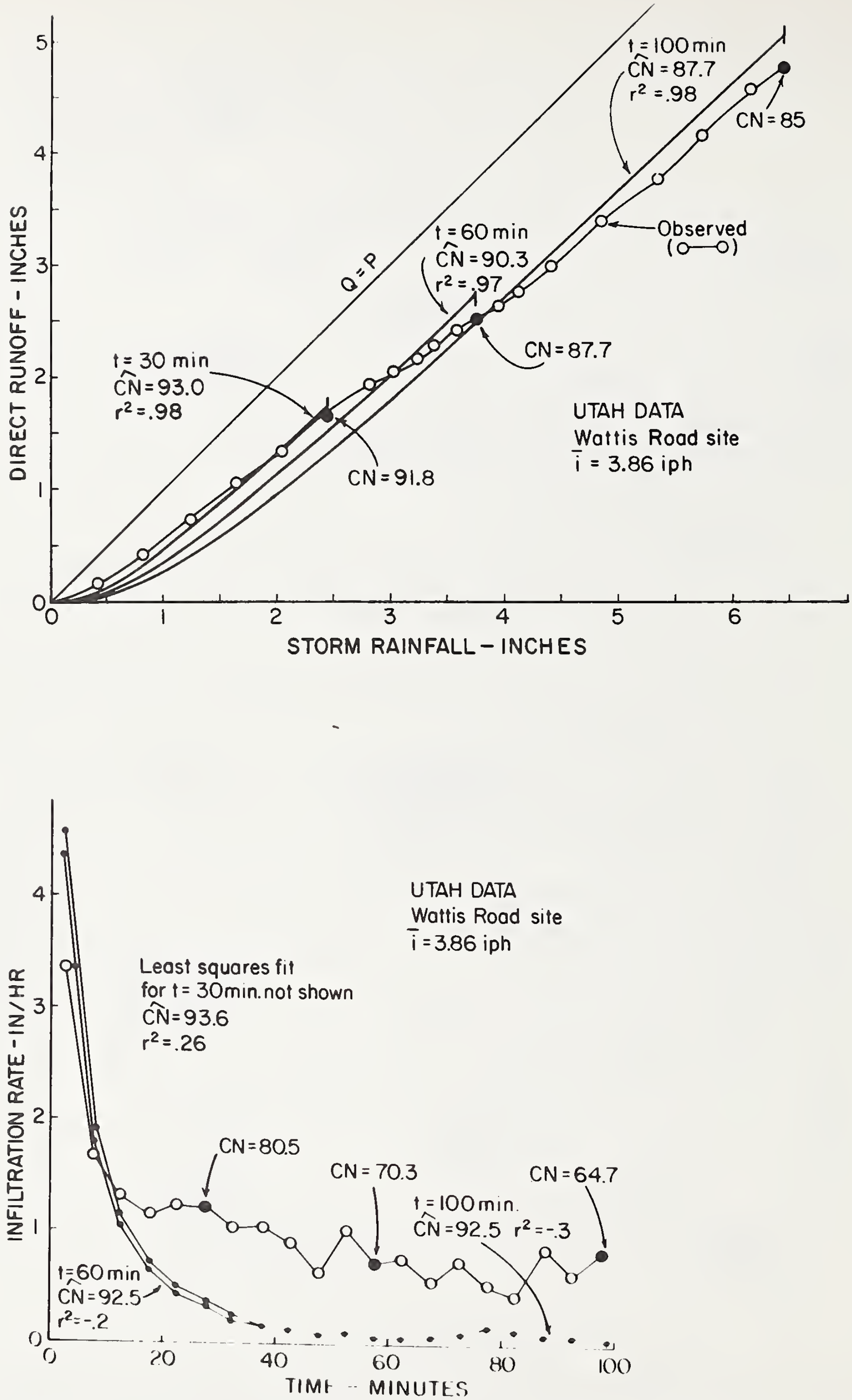


Figure 6. Rainfall, runoff, infiltration, and fitted expression of curve numbers for Utah (Wattis Road) data.

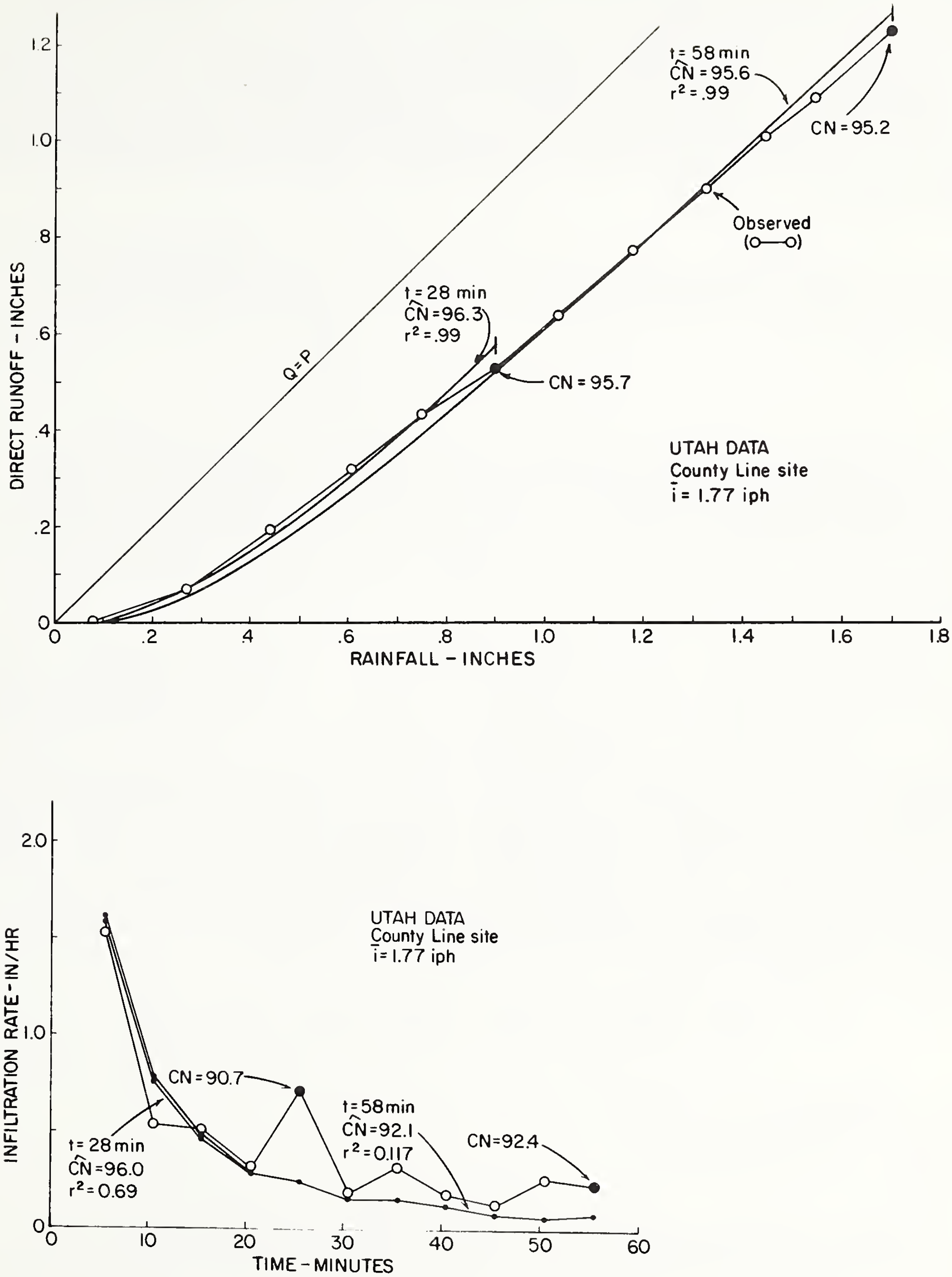


Figure 7. Rainfall, runoff, infiltration, and fitted expression of curve numbers for Utah (County Line) data.

the CN calculated. This is shown for all the data sets studied here, and in the writer's experience, is by far the most common rule of behavior. The plot hydrology metered simply does not match the CN model or its derivatives.

Accordingly, the Georgia data shows CNs from a high of 86 at 30 minutes to a low of 36 at 140 minutes for different methods. Merely within method #2, previously suggested as the least objectionable technique, CN varied from 85 to 77. The Utah data was more encouraging; most of the CNs were found in the 90-96 range, hinting that a high P/S leads to more CN consistent P-Q relationships.

The Arizona data is outstanding in its brevity and scanty runoff, although the same relationships prevail. Applied rain was insufficient to develop the runoff and infiltration processes far beyond the initial thresholds.

Curve Number Assignments

It would not be unexpected for a user-client to ask the ultimate pragmatic question of simulator data: "What is the curve number for this site?" The previous discussion exposes this as a trick question: no answer can be above criticism. Only in unusual situations will the calculated curve number be free of the effects of sampling duration and calculation method. Only at much longer rainfall durations could the infiltration rate realistically be expected to approach zero, and then the calculated curve number stabilize.

While the question will nevertheless persist and demand service, the answer should not be taken in blissful ignorance. Any assignments of curve number should be done with caveats and background stated, based on multiple runs or plots, and with standardization on antecedent moisture condition. The least squares fitting of progressive rainfall and runoff (Method #2) gives the highest impression of reliability, and thus would no doubt generate the most user acceptance. The longest duration sampled is at least closer to an ultimate stable condition, and more representative of the storm durations used in planning efforts. With these cautions in mind, Table 2 shows possible curve numbers for the sites studied. However, the "observed" entries in Table 2 were drawn from only a single run.

CONCLUSIONS, SUGGESTED PROCEDURES AND POLICIES

The preceding experience, although limited, brings several notions to the fore which may profit others in future endeavors. These are briefly covered in the following paragraphs.

Length of Run

Simulator runs should be of sufficient duration to substantially overcome the initial thresholds of runoff. In curve number terms, a high P/S ratio is desired, hopefully to incline observed infiltrations to a stable minimum value, and dQ/dP similarly to a constant slope. This is necessary to affix the degree of conformity of the plot behavior to the curve number function (Equations 1 and 3). Even if the curve number formulation is not assumed

Table 2. Curve number assignments for sites studied.

Site	Runoff curve number		
	Observed from data 1/	Corrected to AMC-II 2/	NEH-4 estimate 3/
Arizona	77.2	89.5	79
Georgia	66.7	82.7	78
Utah			
County Line	95.6	98.5	89
Wattis Road	87.7	95.3	84

Notes: 1/ By least squares fitting of S on progressive rainfall and runoff data. 2/ By interpolation from NEH-4 Table 10.1, assuming runs on a dry (AMC-I) condition. 3/ From given soils and vegetation data and Tables in NEH-4 Chapter 10.

legitimate, sufficient rainfall and runoff is desirable to define a well developed hydrology.

Intensity Measurements

Interim intensity measurements, or interval rainfalls, are more useful and valid data than an assumed constant applied rate. In-storm intensity variations can and do exist, from wind effects and/or mechanical variations, even with well-operated simulators. To the extent that infiltration rates are obtained by differing with observed runoff rates, the variations can influence results. Also, there exists the unresolved, nagging notion that intensity itself may influence infiltration, either in reality as a physical process, or as observed as an apparent phenomenon because of variable "point" infiltration rates across the plot area. Thus, higher resolution (in time) intensity data is a legitimate operational specification.

Rainfall Excess from Runoff

With larger plots, the time consumed in overland flow may cause interval runoff to be inconsistent with measured interval rainfall; observed runoff cannot then be automatically equated to rainfall excess. As illustrated with the Arizona data, intermediate data treatment is necessary to deal with this problem. The approximate procedure described may not be sufficient in all cases.

Curve Numbers

Attempts to wrest curve numbers from simulator data is an assumption-laden exercise, studded with potential disappointments, frustration, and inconsistencies. The most defensible method (least squares fitting on cumulative rainfall and rainfall excess) is at best the "least objectionable" method. The conditions of potential useage should be tightly specified, and estimates suitably couched in disclaimers. Determining curve numbers from field data is analogous to measuring the hat size for a headless horseman.

ACKNOWLEDGEMENTS

This work was supported by the Utah Agricultural Experiment Station, Project 696, "Hydrological Behavior of the Intermountain Forest and Range Lands ...." This is Journal No. 2403 of the Utah Agricultural Experiment Station. Encouragement, critique, and data was supplied freely by the USDA, SEA, Southwest Watershed Research Center, Tucson, Arizona.

LITERATURE CITED

(1) Lusby, G. C. and R. J. Toy.
1976. An evaluation of surface mine spoil area restoration in Wyoming using rainfall simulation. Earth Surface Processes, 1, 375-86.

(2) Hawkins, R. H.
1973. Improved prediction of storm runoff in mountain watersheds. Proc. Am. Soc. Civ. Eng. 99(IR4), 519-23.

(3) Ponce, S. L. and R. H. Hawkins.
1978. Salt Pickup by overland flow in the Price River Basin, Utah. Water Resources Bulletin 14, 5. 1187-1200. (October 1978).

(4) Ponce, S. L.
1975. Evaluation of a non-point source loading function for the Mancos Shale Wildlands of the Price River Basin, Utah. PhD Dissertation, Utah State University, 177 p.

(5) Rawls, W., P. Yates and L. Asmussen.
1976. Calibration of selected infiltration equations for the Georgia Coastal Plain.ARS-S-113. 110 p.

(6) U. S. Department of Agriculture, Soil Conservation Service.
1956. (et seq). National Engineering Handbook, Section 4, Hydrology USGPO, Washington, D.C.

RAINFALL SIMULATION AS A RESEARCH TOOL--
SIMULATION FOR INFILTRATION STUDIES

Roger E. Smith, Hydraulic Engineer
USDA-SEA-AR, Ft. Collins, CO

Infiltration of rain or irrigation water into the soil is one of the most important processes in agricultural hydrology, and the rainfall simulation type infiltrometer is one of the most common means to measure this process. I will confine my remarks to the infiltration aspects of rainfall simulation since others at this workshop are far more experienced in the erosion study use of rainfall simulation. I will comment, however, that the rainfall simulation provided by an intermittent device such as the Purdue Rainulator, while it may be quite useful for erosion studies, does not provide a usable tool for infiltration parameter assessment. Indeed, one could argue that if the simulated rainfall excess pattern is biased, as from an intermittent application, the overall erosion rate simulation will also be biased, irrespective of the accuracy of the simulated rainfall energy.

The best application of an infiltrometer is in estimation or measurement of parameters in a physically-based infiltration model. Such models are presently available. Unfortunately, much labor has gone into infiltrometer work to obtain parameters for empirical formulas, which are useful only for the particular conditions of the infiltrometer run. Further, much infiltrometer work or rainfall simulation work has been done in which insufficient data was collected or inadequate methods were employed to provide soil information needed for today's more versatile, physically related relationships. On the other hand, recent findings in soil physics has prompted some to suggest that laboratory measures of sampled soil properties can be used to construct soil infiltration parameters (Morel-Seytoux and Khanji, 1974). Although this is possible, it is a much more time consuming process and very inefficient. Infiltrometers have the ability to integrate spatial variations and to empirically account in part for vertical nonuniformity. Small infiltrometers which are efficient in use of water may be getting a pseudo-point value from the expected spatially varying soil properties. Without knowledge of soils' spatial scale of random variations the efficient or optimum size of infiltrometer plot cannot be ascertained. This is a subject needing more research.

In this regard, the simple ponded-condition ring infiltrometer is a very useful tool in some soil conditions. This is made possible by the present theory which relates ponded and rainfall infiltration functions. The ring infiltrometer, however, only obtains a point value and should be repeated for a spatially valid sample.

Ponded and sprinkling infiltration conditions are related by reducing the time dependent infiltration rate, $f(t)$, [L/T], to a relation of f and $F = \int f\, dt$. $f(F)$ is closely the same for both conditions. When the rainfall rate, $r(t)$, condition exists, there is an initial time, t_p, in which $f = r$, up to an infiltrated depth F_p. For example, under the Green-Ampt (1911) assumptions, we have

$$f = K_s\left(\frac{DH_c}{F} + 1\right), \quad F > F_p. \tag{1}$$

Under a ring infiltrometer, $F_p = 0$, $f(t=0) = \infty$, and $f(t=\infty) = K_s$. Here K_s is effective saturated conductivity [L/T], D is initial water deficit, $\theta_o - \theta_i$, θ_o is water content at saturation, θ_i is initial water content, and H_c is the Green-Ampt parameter representing "effective capillary head" [L].

A similar relationship exists, which is more appropriate for many soil types (Smith and Parlange, 1978):

$$f = \frac{K_s \exp(F/DH_c)}{\exp(F/DH_c)-1} \tag{2}$$

Surface Routing

In experimental use of infiltrometers, one must recognize first of all what is actually being measured. The rate of runoff at the lower end of the plot is not the difference between rainfall rate and infiltration rate. Furthermore one should recognize that measuring the integrated rate at the outlet of a plot by pumping into a tank with a level recorder involves considerable loss of important detail. What the outflow at the plot outlet represents is the response of a micro-watershed, in which the "rainfall excess" has been routed over the surface, however small or smooth. Figure 1 illustrates the difference between actual $f(t)$ and the value at the plot outfall for several sizes of plot. The surface roughness used was relatively low, representing a sparsely grassed prairie. Notable in this simulation result, produced by the KINGEN model (Rovey, et al., 1977), is the relatively modest difference between the 72 ft (22 m) length plot and the 1 m long plot. Clearly infiltration parameters based on the plot discharge would be biased.

Spatial Variation

Another important factor in interpretation of sprinkling infiltrometer results is the effect of spatial variability of soil parameters. We are certain that soil properties vary across a watershed, all measurements to date indicate that they are log-normally distributed (Smith and Hebbert, 1979), but we do not know for any given soil what are the variance and spatial scale of the dependency. Spatial scale is important in designing the size of the infiltrometer necessary to obtain a statistically valid sample. Variance of K_s for example, influences the bias and distortion we would obtain from an infiltrometer. Figure 2 illustrates this point. This data was obtained by Monte Carlo simulation of composite infiltration rate over an area where K_s varied log-normally. Equation (2) was used to represent f at any point. A similar experiment with rainfall rate higher with respect to K_s shows somewhat diminished relative bias from variance of K_s.

Looking at the results of Figure 2 in a different light, if we had an estimate of the spatial variation or sample distribution of K_s for a soil type, such simulation could be used to obtain a much more accurate value of parameters such as H_c and K_s from an infiltrometer experiment. Likewise, Figure 1 suggests that a good estimate for surface hydraulic roughness and a

surface hydraulic simulation model may be used to improve an estimate of true mean infiltration rate based on infiltrometer measurements. Even recognition of the nature and sense of the bias can help in interpreting infiltrometer data.

Parameter Estimation

Finally, I suggest by the example shown in Figure 3 that optimization methods may be used to obtain parameters H_c and K_s from infiltrometer data, although care must be taken in use of a minimum least squares objective function. Points labeled 1 and 2 have an excessive influence on the optimized curve when minimum $\Sigma\Delta^2$ is used, as the solid line shows. The dot-and-dashed line uses minimized $\Sigma/\Delta \log s/$ (absolute value of the differences in the logarithms of the computed and measured value for f) and obtains a more acceptable fit. Finally, omission of points 1 and 2 gets an even closer fit, although we could argue that given the certain existence of lag due to surface storage as in Figure 1, the dot-dashed line is the best estimate.

The optimization used here is a pattern search technique, adopted for analysis of infiltrometer data after finding that a nonlinear least squares method could not be made to converge with data and functional form as shown. Part of the reason for this may be the excess sensitivity to the larger values of f in the region where the derivative of the function is quite steep.

LITERATURE CITED

(1) Morel-Seytoux, H. J. and Khanji, 1974, "Derivation of an Equation of Infiltration," Water Resources Res., V. 10, No. 4, August, pp. 795-800.

(2) Rovey, E., D. A. Woolhiser, and R. E. Smith, 1977, "A Distributed Kinematic Model of Upland Watersheds," Hydrology Paper No. 93, Colorado State University, Fort Collins.

(3) Smith, R. E., and R. H. B. Hebbert, 1979, "A Monte-Carlo Analysis of the Hydrologic Effects of Spatial Variability of Infiltration," Water Resources Res. (in press).

(4) Smith, R. E., and J-Y. Parlange, 1978, "A Parameter-efficient Hydrologic Infiltration Model," Water Resources Res., V. 14, No. 3, June, pp. 533-538.

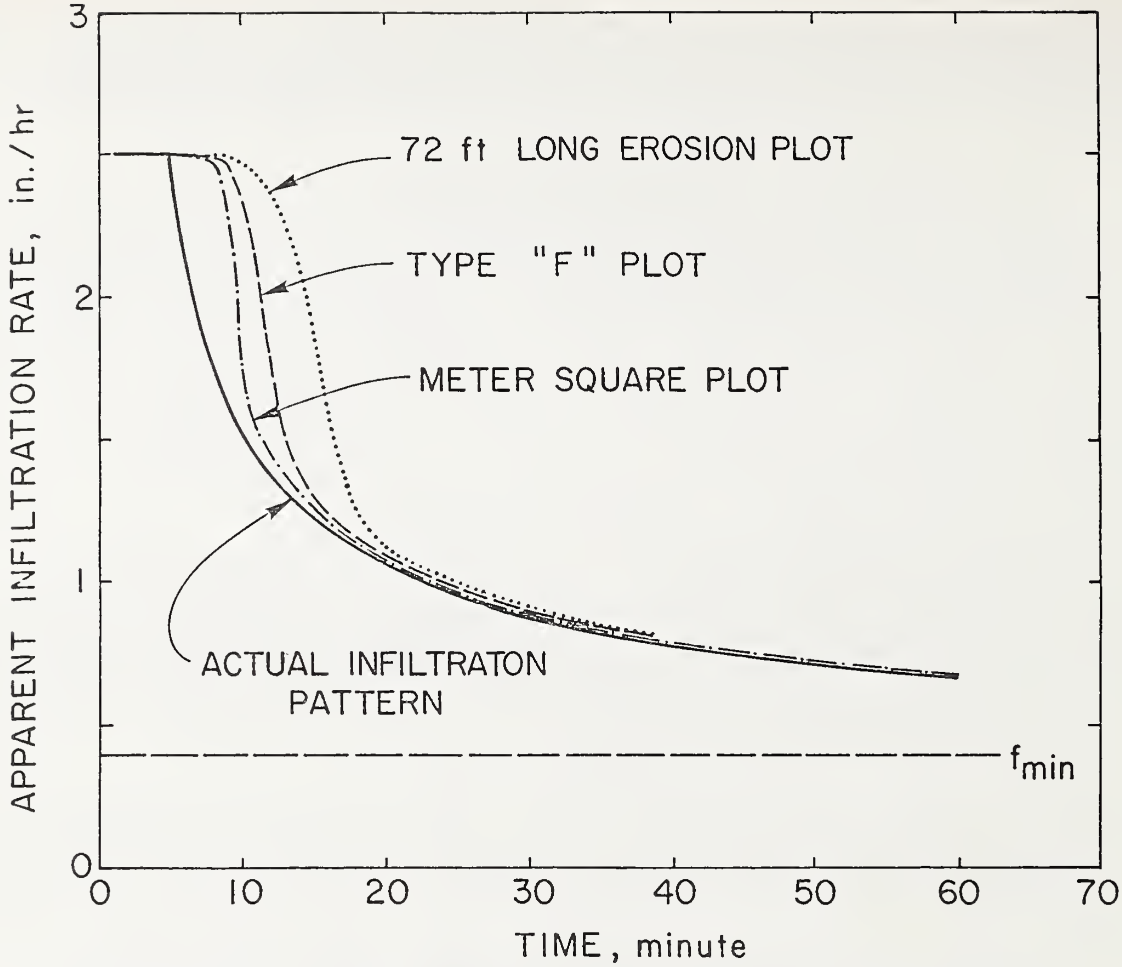


Figure 1. Effect of surface hydraulics on infiltrometer results, simulated with a kinematic hydrologic response model.

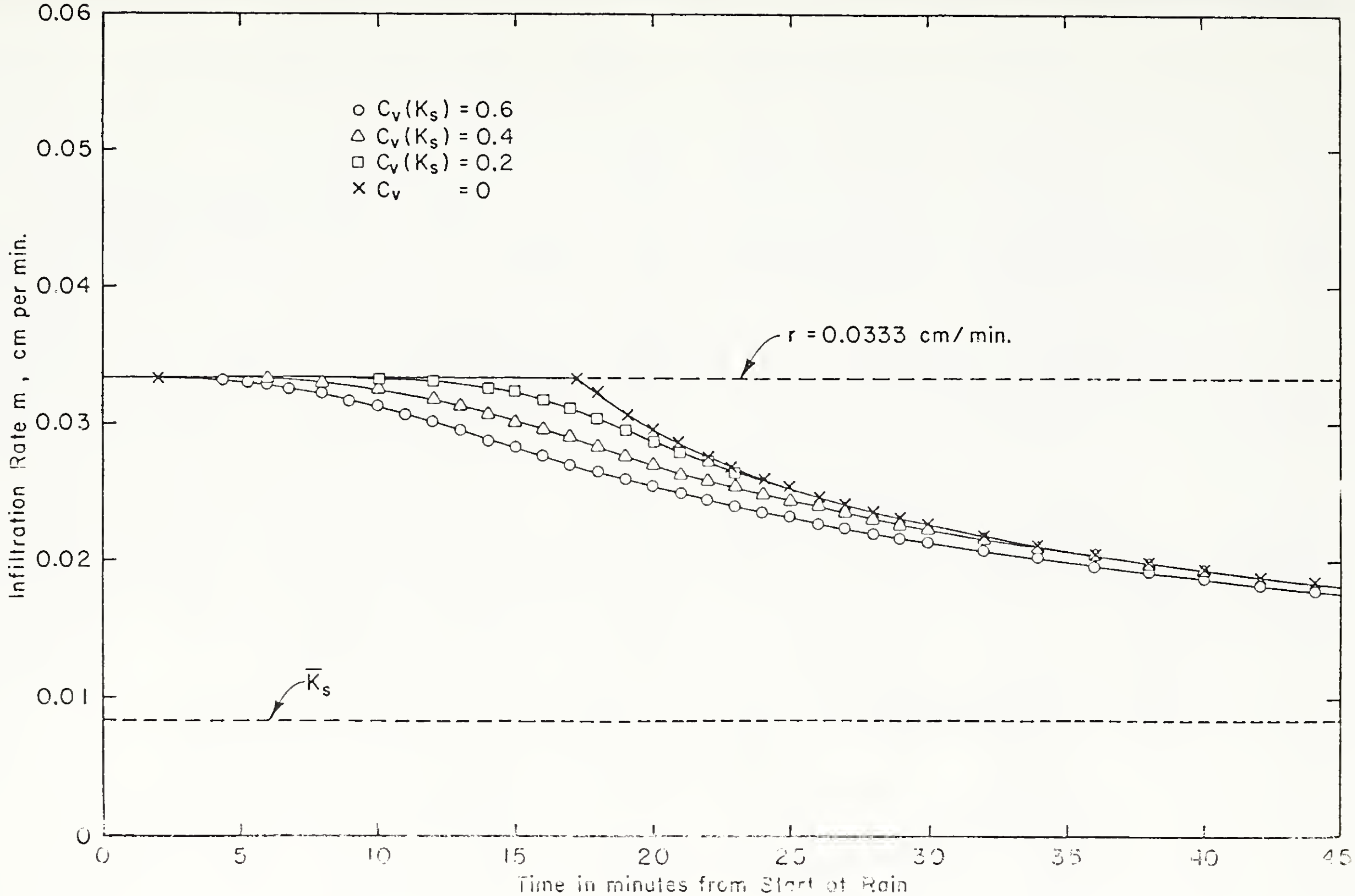


Figure 2. Composite mean infiltration rate pattern for simulated distribution of infiltration rates with a range of c_v, for $r = 4\overline{K}_s$, using the infiltration model of Equation 2.

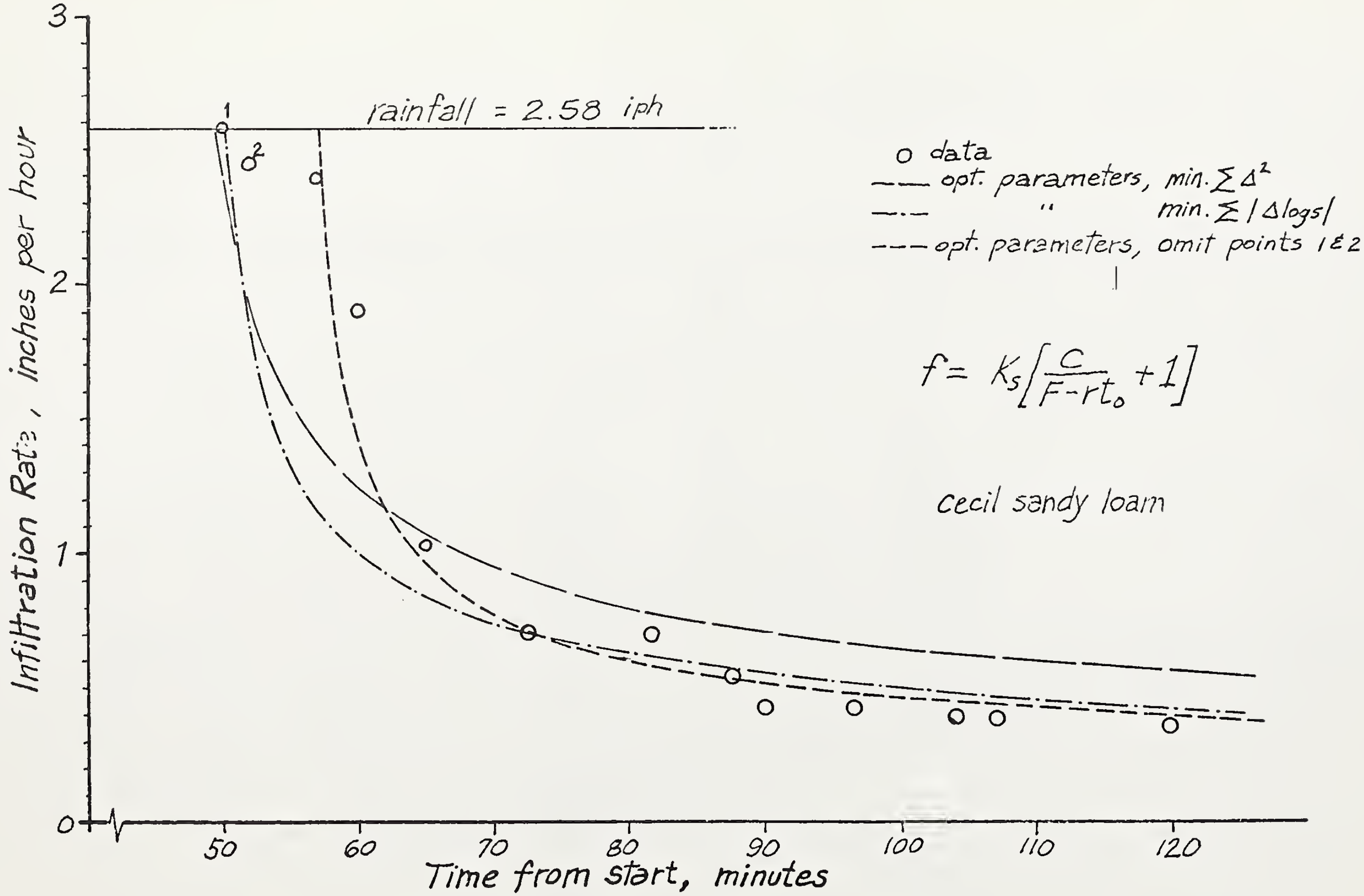


Figure 3. Various optimized fits to obtain infiltration parameters $C = DH_c$ and K_s from infiltrometer data.

RAINFALL SIMULATION AS A RESEARCH TOOL IN INFILTRATION

C. R. Amerman, SEA Research Hydraulic Engineer[1]

INTRODUCTION

The classical concept of infiltration in the hydrologic context is that of the passage of precipitation across the interface between atmosphere and soil. The underlying soil receiving infiltrated water profoundly affects the infiltration process, and most modern work embodies a broadened concept of water moving into and through soil.

Under the latter concept, the hydraulics of infiltration are based on Darcy's law which states that the velocity of water moving in porous media is proportional to the negative of the hydraulic head gradient. In non-saline soils, the effective components of hydraulic head are the pressure head of the soil water and the gravity head due to elevation. Pressure head in unsaturated soil is negative in sign, is a function of water content, and may range over several orders of magnitude as the soil wets or drys.

Hydraulic conductivity is the proportionality coefficient for Darcy's law. It, too, is a function of soil water content and typically varies over several orders of magnitude, being for a given soil, greatest at saturation.

When rainfall begins on a relatively dry soil, a steep hydraulic head gradient is established immediately beneath the soil surface. This leads to an initial hydraulic gradient approaching infinity so that during the early part of a rainfall period, infiltration rate is equal to rainfall intensity - is precipitation controlled. If rain continues to occur at an intensity at least higher than saturated hydraulic conductivity for a long period of time, near-surface hydraulic gradients decrease as the "wetting front" moves deeper and ponding occurs at the soil surface; infiltration from that time is controlled by subsurface hydraulic properties and gradients. During the post-ponding period, the near-surface hydraulic gradient continues to decrease (tends toward unity as soil water content, hence, soil water pressure head, tends towards constancy with depth) and does so more rapidly than hydraulic conductivity increases, with the overall result that infiltration rate decreases with time.

Numerous investigators have attempted to model both the time to ponding and the shape of the post-ponding decay curve. Brakensiek (1979) at a SEA-AR infiltration workshop presented a brief summary of approaches and discussed a few models. With his permission, I have appended his list of references as a fairly comprehensive guide to infiltration model development over the years.

---

[1]USDA, Science and Education Administration, Columbia, MO 65201, in cooperation with the Missouri Agricultural Experiment Station, Columbia, MO

RAINFALL SIMULATION AND INFILTRATION

Rainfall-simulating or sprinkling infiltrometers are often used to obtain representative infiltration curves for various combinations of land surface treatments and soil types.

Sprinkling infiltrometers may also be used to determine the values of parameters used by some infiltration equations. Brakensiek et al. (1977) illustrate the use of an infiltrometer (Hamon, 1979) in obtaining three parameters for the Green and Ampt infiltration equation. Smith and Parlange (1978) present a new two-parameter infiltration equation and indicate how its parameters may be obtained through infiltrometer tests. These are just two of the many examples that could be given.

What are the important points in rainfall simulation in the context of infiltration? Judging from the number of different types of simulators available, and from the fact that ponded water infiltrometers also continue in use, one may conclude that this is a question without a universally accepted answer.

This is probably because, the existence of several fairly successful infiltration models notwithstanding, some details of the infiltration mechanism are poorly understood. For example, there is no way in present models to account for differences in surface condition, except to assume the presence of a thin surface layer of material having a different hydraulic conductivity relation than the underlying soil. So the various investigators may have different opinions as to which precipitation characteristics are significant to infiltration.

One use of infiltrometers, as noted above, is to obtain infiltration model parameters. Unless an infiltration model can account for crusting, or unless its parameters can be conceived as "effective" parameters that reflect surface condition (i.e., an "effective" hydraulic conductivity), there seems little point in attempting to emulate much more than precipitation intensity. Jeppson (1970) constructed a theoretically well-founded infiltration model specificially for use with infiltrometers. This is essentially a state of the art (air flow not considered) model developed around current porous media flow theory and viewing infiltration as either a flux or a zero pressure head (post-ponding) boundary condition on the flow system. Application rate is the only pertinent infiltrometer parameter required by this model.

Brakensiek et al. (1977) used a highly sophisticated sprinkling infiltrometer (Hamon, 1979) to estimate the Green and Ampt equation parameters. Infiltrometer application rates and plot runoff rates were the only parameters of direct interest. The role of precipitation energy in the analyses were not clear, although the authors stressed the ability of the infiltrometer to produce 83% natural rainfall energy. On the other hand, Brakensiek and Onstad (1977) estimated the Green and Ampt parameters from flood infiltrometer data in which neither application rate nor energy plays any part at all. Unfortunately, the two infiltrometers were applied to different soils.

To obtain the Smith and Parlange (1978) equations parameters, one apparently analyzes the infiltration curve obtained by comparing application and runoff rates. Again, the role of precipitation energy is unclear.

The infiltration curve otained from sprinkling infiltrometer data reflects the combined effects of the interactions between precipitation, ground cover, and soil characteristics. Therefore, values of hydraulic conductivity and other parameters obtained from analysis of these curves must also reflect these interactions.

Without detailed knowledge of the above-mentioned interactions, authoritative discussion of precipitation simulation for infiltration studies is not possible. One may discuss extremes with reasonable certainty, but the variation in importance of such a parameter as precipitation energy from one extreme to the other is another matter.

For example, a bare soil tends to puddle and crust, so drop size distribution and velocity in both time and space are probably as important as intensity of application. As energy-dissipating cover becomes more dense, the importance of emulating precipitation energy diminishes until for such conditions as heavy mulches, dense grasses, litter-covered woodland soils, etc., intensity and duration may well be the only important precipitation characteristics.

To be on the safe side, one may simply state that the "best" sprinkling infiltrometer is the one that most nearly emulates natural precipitation - drop size, kinetic energy, average intensity or intensity pattern, duration, temperature, etc. (Incidentally, one seldom sees temperature discussed, and hydraulic conductivity is influenced by temperature. I suspect that for many field infiltrometer tests, neither water nor soil is at temperatures representative of storm conditions.) Of course, in order to be on the safe side, one runs the risk of spending more time and money than is necessary.

The preceding discussion has been slanted toward infiltration model parameter estimation, but the reasoning regarding the relation between soil and cover and which sprinkling infiltrometer characteristics are important applies equally to situations where one wants to empirically compare infiltration curves for different soil-cover-tillage and other conditions.

ON INFILTROMETER APPLICABILITY

Assuming that we have a perfect infiltrometer from the standpoint of emulating all precipitation characteristics except areal coverage, what is the meaning of the infiltration curve that we obtain? Of necessity, a sprinkling infiltrometer of any type applies water to a very small area in comparison to the size of a field or a watershed. The porous media boundary condition imposed by the sprinkling infiltrometer results in an essentially one-dimensional, vertically downward flow system. Even if there is soil layering, the negative of all gradients is essentially away from the infiltrating surface in a psuedo one-dimensional manner. Under natural storm conditions, particularly those producing amounts of water applied in many

sprinkling infiltrometer tests, subsurface flow systems develop that are characterized by hydraulic gradients that are vertical at only a limited number of points. About the only exceptions to this would be very flat areas or such undeveloped profiles as are prevalent in the deep loess areas of southwest Iowa or the central sands of Wisconsin. Klute et al. (1965) illustrate the principle involved. Because infiltration rate is a function of both soil hydraulic conductivity and of soil hydraulic gradient, a sprinkling infiltrometer test must yield a measure of the maximum infiltration rates (curve) to be expected at a given point. During initial periods under actual storm conditions, the hydraulic gradients may be essentially vertical at all locations. As a storm progresses, however, the subsurface flow system develops gradients inclining from the vertical, the infiltration curve probably steepens and drops under the curve obtained with an infiltrometer. In crude "natural infiltrometer" tests on a claypan site in Missouri, I have obtained data that show that for heavy storms, some sites, generally low on a slope, produce more runoff than rainfall, i.e., the subsurface gradients are upward toward the surface. Some of these sites continue to produce runoff (seepage flow) for hours after cessation of precipitation. For the same storms, generally upslope sites produce less runoff than rainfall, and, for lesser storms, all sites infiltrate precipitation throughout the event. Sprinkling infiltrometer tests (modified Purdue type, Dixon and Peterson, 1964, 1968) on all sites produced essentially the same infiltration curves regardless of slope position.

CONCLUDING REMARKS

Rainfall simulation for infiltrometer purposes is not easily prescribed if one wishes to make the most efficient use of resources.

Considering that an infiltrometer-produced infiltration curve is probably a "maximum possible" and that topographic and soil layering effects may obviate its application (in a lumped sense) to a watershed surface, we might conclude that its main utility in comparing different soil-cover-tillage complexes is that of an index rather than that of an absolute quantity. If such be the case, then we might find it most useful to select or develop a standard infiltrometer and operational technique than to dwell on obtaining the best possible simultaneous emulation of all natural precipitation characteristics.

Infiltrometers used in estimating infiltration model parameters must be selected on the basis of the inputs needed by the models.

Infiltrometers used in investigating infiltration mechanisms should themselves be researched. An attempt should be made to assess the nature, or at least the relative importance, of precipitation characteristic-soil-cover interactions. With this type of information, we should be well equipped to design laboratory and/or field infiltrometers for the purpose of isolating the effects upon infiltration of such factors as residue incorporated in surface soil, type of tillage tools, types of vegetation, and so on.

REFERENCES

Brakensiek, D. L.
1979. In C. R. Amerman (ed.) Empirical and simplified infiltration of the Research Planning Workshop. I. State of the Art Reports. SEA-NC Series. (In Press)

Brakensiek, D. L., and C. A. Onstad.
1977. Parameter estimation of the Green and Ampt infiltration equation. Water Resources Res. 13(6):1009-1012.

Brakensiek, D. L., W. J. Rawls, and W. R. Hamon.
1979. Application of an infiltrometer system for describing infiltration into soils. Paper No. 77-2553 presented at 1977 Winter Meeting of American Society of Agricultural Engineers at Chicago, Illinois. Accepted for publication in Am. Soc. Am. Engr.

Dixon, R. M., and A. E. Peterson.
1964. Construction and operation of a modified spray infiltrometer and a flood infiltrometer. University of Wisconsin Res. Report 15. July.

Dixon, R. M., and A. E. Peterson.
1968. Vacuum system for accumulating runoff from infiltrometers. Soil Sci. Soc. Am. Proc. 32(1):123-124.

Hamon, W. R.
1979. Infiltrometer using simulated rainfall for infiltration research. In C. R. Amerman (ed.) Infiltration Research Planning Workshop. I. State of the Art Reports. SEA-NC. (In press)

Jeppson, Roland W.
1970. Transient flow of water from infiltrometers - formulation of mathematical model and preliminary numerical solutions and analyses of results. Utah Water Research Laboratory PRWG-59c-2, Utah State University, Logan. 50 p.

Klute, A., E. J. Scott, and F. D. Whisler.
1965. Steady state water flow on a saturated inclined soil slab. Water Resources Research 1(2):287-294.

Smith, R. E., and J.-Y. Parlange.
1978. A parameter-efficient hydrologic infiltration model. Water Resources Research 14(3):533-538.

RAINFALL SIMULATION AS A RESEARCH TOOL

W. C. Moldenhauer, SEA soil scientist

Rainfall simulation was being used in the early 1930's and continued through the 1940's as reviewed by Mutchler and Hermsmeier (1965). Much of the more recent research began with the development of field rainulators by Meyer and McCune (1958) and later by Swanson (1965). About this time a rain simulator was developed by Bertrand and Parr (1961) for the study of infiltration. A laboratory rain simulator using nozzles was developed by Bubenzer and Meyer (1965) and a drop applicator for basic soil detachment studies was developed by Mutchler and Moldenhauer (1963). Limitations of simulated rainfall as a research tool are pointed out by Mech (1965) --difficulty of extrapolation of results, rainfall simulators complicated and costly to operate, limited by accessibility of water. Advantages are discussed by Meyer (1965) -- more rapid results, standardization of storms, control of plot preparation, use in laboratory to supplement field results. He also discusses development of rain parameters simulated by the Meyer McCune simulator. In spite of limitations, much of the erosion research of the past 20 years has been done with rain simulators and drop applicators. This review is not meant to be complete but will cite examples of much of the research done with rain simulators.

In the area of erosion control research field rain simulators are best suited for study of the effect of tillage and surface covers on soil and water losses. Much research on this has been done in Indiana and has been the basis for cropping factor (C) values based on tillage and surface residue used in the Universal Soil Loss Equation (Wischmeier and Smith, 1978). Examples of research on tillage using field rain simulators are Mannering and Meyer (1961, 1963), Meyer and Mannering (1961, 1963), Mannering et al. (1966), Kramer and Meyer (1969), Moldenhauer et al. (1971), Wischmeier (1973), Laflen et al. (1978) and Johnson and Moldenhauer (1979). Work on this is continuing at Lafayette, Indiana and Ames, Iowa by SEA scientists. Limited research has also been done with field rainulators in testing the effect of row spacing (Mannering and Johnson, 1969) and cropping intensity (Mannering et al., 1968) on soil erosion. The effectiveness of various covers on erosion from highway backslopes (Meyer et al., 1962 and 1970) and construction sites (Meyer et al., 1971) has also been studied.

Water pollution from cropland has been studied using simulated rain by Moe, et al. (1967a, b), Nelson and Romkens (1970), Romkens (1973), Mannering et al. (1978), Bailey et al. (1974) and White et al. (1967).

USDA, Science and Education Administration, AR, Lafayette, Indiana 47907, in cooperation with Purdue University.

Studies of the effect of slope shape on soil loss have allowed considerable refinement of the combined slope length and degree (LS) factor of the Universal Soil Loss Equation. These studies have been made using field rain simulation by Young and Mutchler (1969a, b).

Studies of the effect of soil characteristics on erosion were made to refine the soil factor (K) in the Universal Soil Loss Equation. These were made by Olson et al. (1962) and Wischmeier and Mannering (1969). From many years of field rainulator measurements and analyses of soil characteristics from the soils tested, Wischmeier et al. (1971) developed a nomograph for determining the "K" value from texture, structure, organic matter content and permeability of soils. Roth et al. (1974) also developed a nomograph using iron and aluminum oxides, silica and texture as variables.

More basic studies of erosion mechanics have been made using field rainfall simulators. Studies involving separation of rill from interrill erosion have been made by Young and Mutchler (1969) and by Young and Wiersma (1973). This research is continuing at Lafayette, Indiana.

Particle movement has been studied by both field and laboratory rain simulation. Young and Holt (1968) traced transport and deposition patterns using fluorescent particles. Bubenzer et al. (1966), Foster (1977) all studied particle transport or deposition or both. An important consideration in these studies is size distribution of eroded material. This has been studied using a field rain simulator by Weakly (1962), Swanson et al. (1965), Swanson and Dederick (1967), and Young and Onstad (1976), and with a drop applicator by Gabriels and Moldenhauer (1975). Studies of size distribution of eroded material are continuing at Lafayette, Indiana and Oxford, Mississippi.

Aggregate stability, soil crusting and detachment were studied using a drop applicator by Moldenhauer (1965, 1970), Moldenhauer and Long (1964), Moldenhauer and Koswara (1968), Moldenhauer and Kemper (1969) and Schmidt et al. (1964). The effectiveness of soil conditioners in controlling erosion was determined by Blavia et al. (1971) and Gabriels et al. (1973).

Simulated rain was compared to natural rain by Meyer (1965). Sloneker and Moldenhauer (1974) and Sloneker et al. (1976) studied the effect of intermittency on soil from rain simulated by oscillating nozzles and found problems when a wide range of intensities are simulated because of recovery of soil suction during the off time. Young and Burwell (1972) found, however, very comparable erosion from comparable simulated and natural storms.

Infiltration has been studied recently using the Bertrand and Parr (1961) infiltrometer by Swartzendruber and Hillel (1975). Work is continuing on this at Lafayette, Indiana.

The limitations of field rain simulators pointed out by Mech (1965) are still valid and attempts should be made to develop simulators to overcome these limitations. However, rain simulators as a research tool have long since proved their value. While rain simulation is costly in terms of labor,

much valuable data can be collected in the course of a season. Natural rainfall plots are also costly to operate and data may be years in coming. It is doubtful that we will ever be content to depend on natural rainfall plots again for data. It appears rainfall simulators are here to stay.

LITERATURE CITED

Bailey, G. W., A. P. Barnett, W. R. Payne, Jr., and C. N. Smith. 1974. Herbicide runoff from four Coastal Plain soil types. U.S. Environ. Protection Agency Rep. No. 660/2-74-017.

Bertrand, A. R., and J. F. Parr. 1961. Design and operation of the Purdue sprinkling infiltrometer. Purdue Univ. Agric. Exp. Stn. Research Bull. No 723.

Blavia, F. J., W. C. Moldenhauer, and D. E. Law. 1971. Materials for stabilizing surface clods of cropped soils. Soil Sci. Soc. of Am. Proc. 35:119-122.

Bubenzer, G. D., and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans. Am. Soc. Agric. Engrs. 8:73-75.

Bubenzer, G. D., L. D. Meyer, and E. J. Monke. 1966. Effect of particle roughness on soil erosion by surface runoff. Trans. Am. Soc. Agric. Engrs. 9(4):562-564.

Foster, G. R., and L. D. Meyer. 1972. Transport of soil particles by shallowflow. Trans. Am. Soc. Agric. Engrs. 15(1):99-102

Foster, G. R., and L. F. Huggins. 1977. Deposition of sediment by overflow on concave slopes. In George Foster (ed.) Soil Erosion: Prediction and Control. Soil Conserv. Soc. of Am., Ankeny, Iowa. p. 167-180.

Gabriels, D. M., W. C. Moldenhauer, and Don Kirkham. May-June 1973. Infiltration, hydraulic conductivity and resistance to waterdrop impact of clod beds as affected by chemical treatment. Soil Sci. Soc. of Am. Proc. 37.

Gabriels, D. M., and W. C. Moldenhauer. 1978. Size distribution of eroded material from simulated rainfall: Effect over a range of texture. Soil Sci. Soc. Am. J. 42:954-958.

Johnson, C. B., and W. C. Moldenhauer. 1979. Effect of chisel versus moldboard plowing on soil erosion by water. Soil Sci. Soc. Am. J. 43(1):( ). (In press)

Kramer, L. A., and L. D. Meyer. 1969. Small amounts of surface mulch reduce soil erosion and runoff velocity. Trans. Am. Soc. Agric. Engrs. 12(5):639-641.

Laflen, J. M., J. L. Baker, R. O. Hartwig, W. F. Buchele, and H. P. Johnson. 1978. Soil and water loss from conservation tillage systems. Trans. Am. Soc. Agric. Engrs. 21:881-885.

Mannering, J. V., and C. B. Johnson. 1969. Effect of crop row spacing on erosion and infiltration. Agron. J. 61:902-905.

Mannering, J. V., and L. D. Meyer. 1961. The effects of different methods of cornstalk residue management on runoff and erosion as evaluated by simulated rainfall. Soil Sci. Soc. Am. Proc. 25:506-510.

Mannering, J. V., L. D. Meyer. 1963. The effects of various rates of surface mulch on infiltration and erosion. Soil Sci. Soc. Am. Proc. 27:84-86.

Mannering, J. V., L. D. Meyer, and C. B. Johnson. 1966. Infiltration and erosion as affected by minimum tillage for corn (Zea mays L.). Soil Sci. Soc. Am. Proc. 30(1):101-105.

Mannering, J. V., L. D. Meyer, and C. B. Johnson. 1968. Agron. J. 60:206-209.

Mannering, J. V., D. W. Nelson, and C. B. Johnson. 1978. Environmental impact of cropland agriculture on water quality. To be published in Workshop Assessment of Erosion in U.S.A. and Europe, Ghent, Belgium, Feb. 27-March 3.

Mech, S. J. 1965. Limitations of simulated rainfall as a research tool. Trans. Am. Soc. Agric. Engrs. 8:66-67.

Meyer, L. D. 1965. Simulation of rainfall for soil erosion research. Trans. Am. Soc. Agric. Engrs. 8:63-65.

Meyer, L. D., C. B. Johnson, and G. R. Foster. 1972. Sonte and woodchip mulches for erosion control. J. Soil Water Conserv. 27(6):264-269.

Meyer, L. D., and J. V. Mannering. 1963. Crop residues as surface mulches for controlling erosion on sloping land under intensive cropping. Trans. Am. Soc. Agric. Engrs. 6:322, 323, 327.

Meyer, L. D., and J. V. Mannering. 1961. Minimum tillage for corn, its effect on infiltration and erosion. Agric. Engr. 2:72-75.

Meyer, L. D., and D. L. McCune. 1958. Rainfall simulator for runoff plots. Agric. Engr. 39:644-648.

Meyer, L. D., W. H. Wischmeier, and W. H. Daniel. 1971. Erosion, runoff and revegetation of denuded construction sites. Trans. Am. Soc. Agric. Engrs. 14:138-141.

Meyer, L. D., W. H. Wischmeier, and G. R. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Sci. Soc. Am. Proc. 34:928-931.

Moe, P. G., J. V. Mannering, and C. B. Johnson. 1967a. A comparison of nitrogen losses from urea and ammonium nitrate in surface runoff water. Soil Sci. 105:428-433.

Moe, P. G., J. V. Mannering, and C. B. Johnson. 1967b. The loss of fertilizer nitrogen in surface runoff water. Soil Sci. 104:389-394.

Moldenhauer, W. C. 1965. Procedure for studying soil characteristics using disturbed samples and simulated rainfall. Trans. Amer. Soc. Agric. Engrs. 8:74-75.

Moldenhauer, W. C. 1970. Influence of rainfall energy on soil loss and infiltration rates: II. Effect of clod size distribution. Soil Sci. Soc. Am. Proc. 34(4):673-677.

Moldenhauer, W. C., and W. D. Kemper. 1969. Interdependence of water drop energy and clod size on infiltration and clod stability. Soil Sci. Soc. Am. Proc. 33(2):297-301.

Moldenhauer, W. C., and Jajah Koswara. 1968. Effect of initial clod size on characteristics of splash and wash erosion. Soil Sci. Soc. Am. Proc. 32:875-879.

Moldenhauer, W. C., and D. C. Long. 1964. Influence of rainfall energy on soil loss and infiltration rates: I. Effect over a range of texture. Soil Sci. Soc. Am. Proc. 28:813-817.

Moldenhauer, W. C., W. G. Lovely, N. P. Swanson, and H. D. Currence. 1971. Effect of row grades and tillage systems on soil and water losses. J. Soil Water Conserv. 26:193-195.

Muchler, C. K., and L. L. Hermsmeier. 1965. A review of rainfall simulators. Trans. Am. Soc. Agric. Engrs. 8(1):67-68.

Neibling, W. H., and G. R. Foster. 1977. Estimating deposition and sediment yield from overland flow processes. Proc. of International Symposium on Urban Hydrology, Hydraulics, and Sediment Control, University of Kentucky, Lexington, KY - July 18-21.

Nelson, D. W., and M. J. M. Romkens. 1970. Transport of phosphorus in surface runoff. Proc. Cornell Conf. on Agric. Waste Manage. p. 215-225.

Olson, T. C., J. V. Mannering, and C. B. Johnson. 1962. The erodibility of some Indiana soils. Proc. Ind. Acad. Sci. 72:319-324.

Romkens, M. J. M., D. W. Nelson, and J. V. Mannering. 1973. Nitrogen and phosphorus composition of surface runoff as affected by tillage method. J. Environ. Qual. 2:292-295.

Roth, C. B., D. W. Nelson, and M. J. M. Romkens. 1974. Prediction of subsoil erodibility using chemical, mineralogical and physical parameters. U.S. Environ. Protection Agency Rep. No. 660/2-74-043. 111 p.

Schmidt, B. L., W. D. Shrader, and W. C. Moldenhauer. 1964. Relative erodibility of three loess-derived soils in Southwestern Iowa. Soil Sci. Soc. Am. Proc. 28:570-574.

Sloneker, L. L., and W. C. Moldenhauer. 1974. Effect of varying the on-off time of rainfall simulator nozzles on surface sealing and intake rate. Soil Sci. Soc. Am. Proc. 38:157-158.

Sloneker, L. L., T. C. Olson, and W. C. Moldenhauer. 1976. Effect of pore water pressure on sand splash. Soil Sci. Soc. Am. J. 40:948-951.

Swanson, N. P. 1965. Rotation-boom rainfall simulator. Trans. Am. Soc. Agric. Engrs. 8:71-72.

Swanson, N. P., and A. R. Dedrick. 1967. Soil particles and aggregates transported in water runoff under various slope conditions using simulated rainfall. Trans. Am. Soc. Agric. Engrs. 10:246-247.

Swanson, N. P., A. R. Dedrick, and H. E. Weakly. 1965. Soil particles and aggregates transported in runoff from simulated rainfall. Trans. Am. Soc. Agric. Engrs. 8:437, 440.

Swartzendruber, D., and D. Hillel. 1975. Infiltration and runoff for small field plots under constant intensity rainfall. Water Resour. Res. 11:445-451.

Weakly, H. E. 1962. Aggregation of soil carried in runoff from simulated rainfall. Soil Sci. Soc. Am. Proc. 26:511-512.

White, A. W., A. P. Barnett, B. G. Wright, and J. H. Holladay. 1967. Atrazine losses from fallow land caused by runoff and erosion. Environ. Sci. and Technol. 1:740-744.

Wischmeier, W. H. 1973. Conservation tillage to control water erosion. Proc. Natl. Conserv. Tillage Conf., March 1973, Soil Conserv. Soc. Am. p. 133-141.

Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv. 26(5):189-193.

Wischmeier, W. H., and J. V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33:131-137.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses - A guide to conservation planning. U.S. Dept. of Agric. Agriculture Handbook 537.

Young, R. A., and R. F. Holt. 1968. Tracing soil movement with fluorescent glass particles. Soil Sci. Soc. Am. Proc. 32:600-602.

Young, R. A., and C. K. Mutchler. 1969a. Effect of slope shape on erosion and runoff. Trans. Am. Soc. Agric. Engrs. 12:231-233, 239.

Young, R. A., and C. K. Mutchler. 1969b. Soil and water movement in small tillage channels. Trans. Am. Soc. Agric. Engrs. 12:543-545.

Young, R. A., and C. K. Mutchler. 1969c. Soil and water movement on irregular slopes. Water Resour. Res. 5:1084-1089.

Young, R. A., and C. A. Onstad. 1976. Predicting particle-size composition of eroded soil. Trans. Am. Soc. Agric. Engrs. 19:1071-1075.

Young, R. A., and J. L. Wiersma. 1973. The role of rainfall impact in soil detachment and transport. Water Resour. Res. 9:1629-1636.

Young, R. A., and R. E. Burwell. 1972. Prediction of runoff and erosion from natural rainfall using a rainfall simulator. Soil Sci. Soc. Am. Proc. 36:827-830.

INTERPRETATION OF RAINFALL SIMULATOR DATA

M. J. M. Römkens[1]

A short discussion is given concerning the impact of rainfall simulation practices on data interpretation. This summary consists of a discussion of the impact of storm characteristics, soil characteristics, rainfall simulator size, and computational procedures on acquired rainfall simulator data. This discussion is implicit in character and "spotlights" some of the consequences of using rainfall simulation equipment and approaches.

PERSPECTIVE

For many years the predominance of rainfall simulation research has focused either on the development of rainfall simulation equipment or on evaluations of the statistically based factor relationships in the USLE. Future research emphasis will relegate these aspects to a level of reduced importance. The need and interest in developing and refining rainfall simulation equipment and improving existing factor relationships of the USLE will remain, but the emphasis will shift to a process and property oriented research. The danger of this shift in emphasis will be a fragmentation and duplication of research without the essential integration of the individual efforts. In any case, there will be increased need for a truly multiple disciplinary approach, in which individual interest are subordinated to the common interest. The net impact of such an approach on future rainfall simulation will be (i) to set higher technical requirements on the type of rainfall simulators to be used, (ii) to better formulate research objectives within the context of the overall erosion research efforts, (iii) to improve in the execution of research objectives, and (iv) to perfect and improve our analytical capabilities.

EFFECT OF STORM CHARACTERISITCS

The effect of storm simulation on soil erosion are due to differences in the type of rainfall simulator used and the storm characteristics imparted. These differences consist of variations in temporal and spatial intensity distributions, drop size and drop size distribution, intermittancy of rain application, velocity and angle of drop impact etc. A summary of the problems of incorporating natural rainfall

1/ Soil Scientist (Physics), USDA Sedimentation Laboratory, Oxford, MS 38655.

characteristics into rainfall simulator design has been given by L. D. Meyer (1958). Additional information may be found elsewhere in the Proceedings of this Conference [See C. K. Mutchler's paper: "Geographical (Regional) Differences in Rainfall Characteristics"]. Anyhow, many of these characteristics are interrelated. For instance a change in intensity will usually go hand in hand with a shift in drop size distribution and consequently different energies. For natural rainstorms these variations were accounted for in the correlation of the EI_{30}-factor on soil loss from bare runoff plots. With the introduction of simulated rainfall equipment, i.e. the large field size rainulator described by Meier and McCune (1958), the rainfall intensity I is constant and the kinetic energy E is proportional to the product of rainfall duration (D) and rainfall intensity (I). The net result is a proportionality between soil loss and I^2. This relationship has subsequently been used in corrections for soil loss at simulated intensities different from the arbitrarily defined 2.5 inch per hour reference intensity. In rainfall simulator designs with different types of nozzles, changes in the drop size distribution should be determined to arrive at the proper E-value. The EI value thus obtained should then be a basis for computing soil erosion rates. A second difference with natural rainstorms is the necessity of intermittent rain applications in order to stay within reasonable application rates. The local concentration of rain on the soil surface in those simulator designs has a pulsating effect on the transport of soil particles as well as an enhanced effect on soil detachment by localized flow concentrations. The ultimate impact of these factors on soil loss has not been adequately assessed. Nevertheless, they contribute to the error in soil loss computations. Rainfall simulators with stationary nozzles concentrates rain in localized areas unlike the evenly distributed rain pattern of natural rainfall. Hence, differences in soil loss between natural and simulated storms under otherwise similar conditions of rainfall amount, intensity, and soil medium is to be expected.

EFFECT OF SOIL CHARACTERISTICS

Comparative little information is available concerning the quantitative effect of differences in soil media and temporal variations in antecedent conditions for a particular soil. In a broad sense, these effects were accounted for in the derivation of K-factors and C-factors by averaging out temporal variations in soil susceptibility to detachment and transport. The rainulator described by Meyer and McCune (1958) has been extensively used to arrive at absolute values of K-factors and C-factors within the context of the USLE. Extreme care must be given however to an accurate procedural execution of measurements and a proper evaluation of the antecedent state of the soil vs. à vis. moisture content, residue, and surface roughness, degree and uniformity of slope, as well as a properly applied rainstorm. Even then, an adequate number of replications is required to minimize error due to randomness. Many of the field rainulator studies, often involving unit-plot[2/] sizes, did not attend very well to these requirements. Often, weather, land preparational

2/ Unit plot refers to a 6 by 72.6 foot plot of 9% slope as defined in the USLE.

limitations, and cost factors did not permit an optimal execution of experiments. In any case, in interpreting the measured soil losses corrections should be made for those variations. However, relationships to make these corrections are not available, thereby introducing often significant errors. The greatest advantage of the aforementioned field rainulator is in comparative evaluations of management treatments.

Rainulator studies involving laboratory type rainfall simulators require the transport of soil to the laboratory. In these studies, significant departures from natural conditions of antecedent conditions, degrees of compaction, aggregate size distribution, and above all a finite soil depth, which severely may affect the infiltration component, are obtained. In short, the soil material, which usually has been air dried, will respond differently to erosive agents in the Laboratory than under similar storms in the field.

EFFECT OF RAINFALL SIMULATOR SIZE

Several types of rainfall simulators are currently in use. A summary of the various types of rainfall simulators and their characteristics has been given elsewhere in the Proceedings of this Conference (See G. D. Bubenzer: "Rainfall Characteristics Important for Simulation). On an areal basis, four types rainfall simulators may be distinguished: (i) Large areal (watershed size) rain applicators consisting of rainjet type nozzles placed on 10 feet or higher upright irrigation pipes which are placed in a rectangular gridwork. This simulator, developed at Colorado State University by R. E. Smith and co-workers, may be an effective tool to study hydrologic responses of field size watershed, but is inadequate for soil erosion investigations from the viewpoint of simulating rainfall energy. (ii) The Meyer-McCune type rainfall simulator which has been extensively used in evaluations of USLE factor relationships. This rainfall simulator covers plot sizes of 6 by 72.6 feet and smaller. (iii) The Purdue-type infiltrometer covering plot areas of 10 by 10 feet. This rainfall simulator may have spray type nozzles or drop formers. (iv) The laboratory rainfall simulators or rain applicators, usually consisting of drop formers, covering small experimental areas of 1 by 1 foot or smaller. Experiments with rainfall simulators, which apply rain to small experimental areas (100 ft^2) or smaller are unacceptable for direct evaluations of terms in the USLE. Small field and laboratory rainulators do not permit the incorporation of the runoff component in the soil erosion process. Small field and laboratory rainfall simulators may be extremely useful, however, in the analytical evaluation of soil detachment, parametric equations, infiltration, and runoff chemistry. The areal coverage for this type of equipment should be within a range of 4 to 10 ft^2. Laboratory simulators covering smaller areas are extremely useful in evaluating specific soil physical and soil chemical effects such as surface sealing and soil detachment effects by chemicals. Since most attention in soil erosion research concerns the evaluation of factor relationship in the USLE, rainfall simulators covering at least a 200 ft^2 soil area should be used.

DIFFERENCES IN COMPUTATIONAL PROCEDURES

The procedures used in evaluating USLE factors are well established. The topographic factor is usually evaluated by established relationships for slope length and slope-gradient, even though the data base on which these relationships are based is extremely small. C-factors are determined relative to soil loss from unit plot size and unit plot conditions as reflected by the K-factor. Hence, accurate K-factor determinations are extremely important. Comparing rainulator data with data from natural runoff plots may provide a basis for computation procedures. This in fact was done in determining the soil erodibility nomograph in which properties were used as the correlators. However this approach is only valid if one deals with soils of the same general textural composition and genetic origin. The literature has a number of publications dealing with K-factor evaluations, which were carried out according to different procedures (Barnett and Rogers, 1966; Wischmeier and Mannering, 1969; Wischmeier et al., 1971, El-Swaify and Dangler, 1976; Romkens et al., 1977; Young and Mutchler, 1977). Significant differences exists between these evaluations although the same type rainfall simulator was used.

CONCLUSIONS

Interpretation of rainulator data should be done within the context of the type of rainulators used. Derivations and refinements of the factor relationship in the USLE will need continuous use of large areal field simulators such as the Meyer-McCune type rainulator presently used or a modification thereof (see G. R. Foster's contribution to this Conference: "Recent Developments in Simulator Design"). Analytical approaches to evaluate these factors may be carried out by improved simulator designs which are more process specific and may cover small experimental areas. Ultimately, improved erosion process simulation will not be decided by the type of rainulator used, but by improved perception, problem definition, procedural refinements and data analysis. The rainulator per se will be of course the *sine qua non* for any good experimental investigation.

LITERATURE CITED

(1) Barnett, A. P., and J. L. Rogers.
1966. Soil physical properties related to runoff and erosion from artificial rainfall. Trans. ASAE 9:123-125, 128.

(2) El-Swaify, S. A. and E. W. Dangler.
1976. Erodibilities of selected tropical soils in relation to structural and hydrologic parameters. Proc. Ntl. Conf. on Soil Erosion. West-Lafayette, Indiana, pp. 105-114.

(3) Meyer, L. D.
1958. The investigation of method for simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles. USDA-ARS-SWC, Special Report No. 81.

(4) Meyer, L. D. and D. L. McCune.
1958. Rainfall simulator for runoff plots. Agr. Eng. 39:644-648.

(5) Romkens, M. J. M., C. B. Roth, and D. W. Nelson.
1977. Erodibilities of selected clay subosils in relation to physical and chemical properties, J. Soil Sci. Soc. Am. 41:956-960.

(6) Wischmeier, W. H., C. B. Johnson, and B. V. Cross.
1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Conserv., 26:189-193.

(7) Wischmeier, W. H. and J. V. Mannering.
1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33:131-137.

(8) Wischmeier, W. H. and D. D. Smith.
1965. Predicting rainfall-erosion loss from cropland east of the Rocky Mountains. Agr. Handbook No. 202. U. S. Dept. of Agr., Washington, D.C., 47 pp.

INTERPRETATION OF RAINFALL SIMULATOR DATA

By John M. Laflen, agricultural engineer[1/]

Interpretation is the act of setting forth the meaning of something, in this case, the meaning, with respect to the "real" world, of a particular set of data collected during an experiment where rainfall was provided by a simulator. The question here is "how closely does the real world conform to how we predict it will perform, based on a rainfall simulator study".

The question above is important to every research study. Questions about extrapolation of results in hydrologic studies include questions about plot size, rainfall characteristics, uniformity (or nonuniformity) of plot with regard to slope, soils, vegetation, residue, surface condition, etc., and are as important to natural rainfall studies as to rainfall simulator studies. For example, if one accepts the premise that soil erosion is proportional to EI, data by McGregor and Mutchler (1977) indicate an extremely wide range in EI for a single value of the variable usually measured, I. Their data indicate there is no single value of E for a measured value of I. How do you interpret results from such studies, and how safely can they be extrapolated?

I'll confine my discussion to situations where we're searching for relations expressing the impact of independent variables on soil erosion from the standpoint of application in the USLE. Such studies usually involve growing crops, crop residue, and different cropping stages. I'll discuss only 2 items, test procedures and plot size.

TEST PROCEDURES

It has been "traditional" to use test procedures whereby a series of runs on a plot are conducted within a short time. These sometimes are a "dry" run, followed by a period of several hours with no rain, then a "wet" run, and very shortly afterward, a "very wet" run. Not all runs are always at the same rainfall intensity. This procedure makes it very difficult to evaluate a large number of replicated treatments where cropping and antecedent conditions are virtually unchanged within an experiment. Additionally, such large amounts of rainfall and runoff may negate the use of the same plot for studies later in the season. Extrapolation to real world situations is difficult. What measurement do you use? Do you, as Wischmeier and Mannering (1969) did, arrange the storms so as to get a value representing the EI over an extended period? Aren't there interactions of independent

---

1/ Science and Education Administration, Agricultural Research, U.S. Department of Agriculture, Ames, IA 50011

variables such as rainfall amount, intensity, antecedent moisture, and other soil and crop factors?

An example of such interactions is shown in Figures 1 and 2. Each line shown is from two replicates where a rotating boom rainfall simulator was operated over 10' x 35' plots. Accumulated soil erosion was related to percent of the surface covered with crop residue by an equation of the form

$$\text{Erosion} = ae^{b \cdot \text{cover}} \tag{1}$$

after rainfall applications of 20, 40, 60, and 80 minutes. The preceding crop was corn. Rainfall intensity was 2.5 inches per hour. A final erosion rate was also related to cover using equation 1. The mulch factor shown is equation (1) divided by a, the erosion rate expected for no residue cover. Note that in Figure 1, as time proceeded, the effect of residue cover became less pronounced, while in Figure 2, it became more pronounced. Figure 1 and 2 are for 1977 data, when canopy was small (late cropping period 1, or early period 2). The same trends were observed for two tests in 1978 when canopy was significant, and when either corn or beans was the preceding crop. The WIEF location had steep slopes (12%) and was on a loessial soil, while the Ames location had a flat slope (5%), and the soil was high in sand. Runoff amounts were not well correlated with residue cover. In neither case was antecedent soil moisture high. I believe the differences were related to slopes and soils, and to the difference in resistance to rill and interrill erosion between the soils. What variable and at just what time do you select to make comparisons of treatments? Short, high intensity storms, if antecedent moisture is not high, are likely similar to the earlier relations shown in Figures 1 and 2. The kind of factor relationship you arrive at, based on analysis of rainfall simulator data, could depend greatly on the test procedure used.

PLOT SIZE

Much has been made of the small size of rainfall simulator plots. These plots range in size from 1 m square to over 70 ft. long (unit plot length). We have overcome these limitations for up-and-down hill rows using theory derived by Foster et al (1977). They derived an equation for rill erosion down a slope of length x when sediment load is not near transport capacity, and sediment detachment is not a function of sediment load. Detachment was a function of tractive force (critical tractive force was assumed to be zero), and steady state conditions were assumed. Then rill erosion was expressed as

$$G_r = K_r x^2 \tag{2}$$

where G_r is total rill erosion on the length x, and K_r is a constant. The rill erosion on the lowest length L of x is

$$G_{rL} = K_r[x^2 - (x-L)^2] \tag{3}$$

or

$$G_{rL} = -K_r L^2 + 2K_r Lx \quad (4)$$

If interrill erosion is not a function of length, then total interrill soil loss (G_{IL}) from a length L can be expressed as

$$G_{iL} = K_i L \quad (5)$$

and total erosion from length L (G_L) could be written as

$$G_L = L(K_i - K_r L) + 2K_r Lx \quad (6)$$

or

$$G_L = a + bx \quad (7)$$

the equation of a straight line.

Experimentally, our procedure has been to operate the simulator until runoff is near equillibrium. Then, clear water is added at one rate across the plot width. When runoff rate stabilizes, samples are collected, and flow rates measured. Flow rates are incremented upward with samples and measurements after each increment. Row length (x) is the length that would generate the runoff rate per unit area when runoff was near equillibrium with the simulator alone operating.

Linear regressions are then performed to determine values of K_r and K_i. Total erosion can then be related to independent variables for lengths of interest, or the effect on K_r and K_i of various independent variables can be examined.

Our experience has been that the assumptions Foster et al (1977) made in deriving equation 2 are valid for the steady state conditions we have been examining. We are still in the midst of relating K_r and K_i to residue cover and canopy. One of these relations (subject to future modification) of K_r to residue cover is shown in Figure 3.

The experimental conditions when simulating length leave much to be desired. In some cases, erosion is so severe as to raise serious question about the results. The assumptions of Foster et al (1977) need further investigation.

When rows are on the contour, and plots are small (narrow) extrapolation to larger lengths or wider plots is uncertain. So far, we've not come up with a good procedure.

SUMMARY

Test procedures have an impact on the results of analysis of rainfall simulator data. Interpretation of these data should proceed only with a knowledge of just how the relation of soil erosion to various independent

variables changes with time. Extrapolation to field conditions of derived relations can be made when data are carefully analyzed.

We have simulated row length in rainfall simulation studies. The results are especially meaningful when analyzed in the light of recent advances in erosion mechanics. Plot size is a limitation in every erosion study, whether under natural or artificial rainfall conditions.

LITERATURE CITED

Foster, G.R., L.D. Meyer, and C.A. Onstad. 1977. An erosion equation derived from basic erosion principles. Trans. Am. Soc. Agric. Eng. 20:678-682.

McGregor, K.C. and C.K. Mutchler. 1977. Status of the R factor in northern Mississippi. In: Soil Erosion: Prediction and Control. Soil Conservation Society of America Special Publication No. 21.

Wischmeier, W.H. and J.V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. 33:131-137.

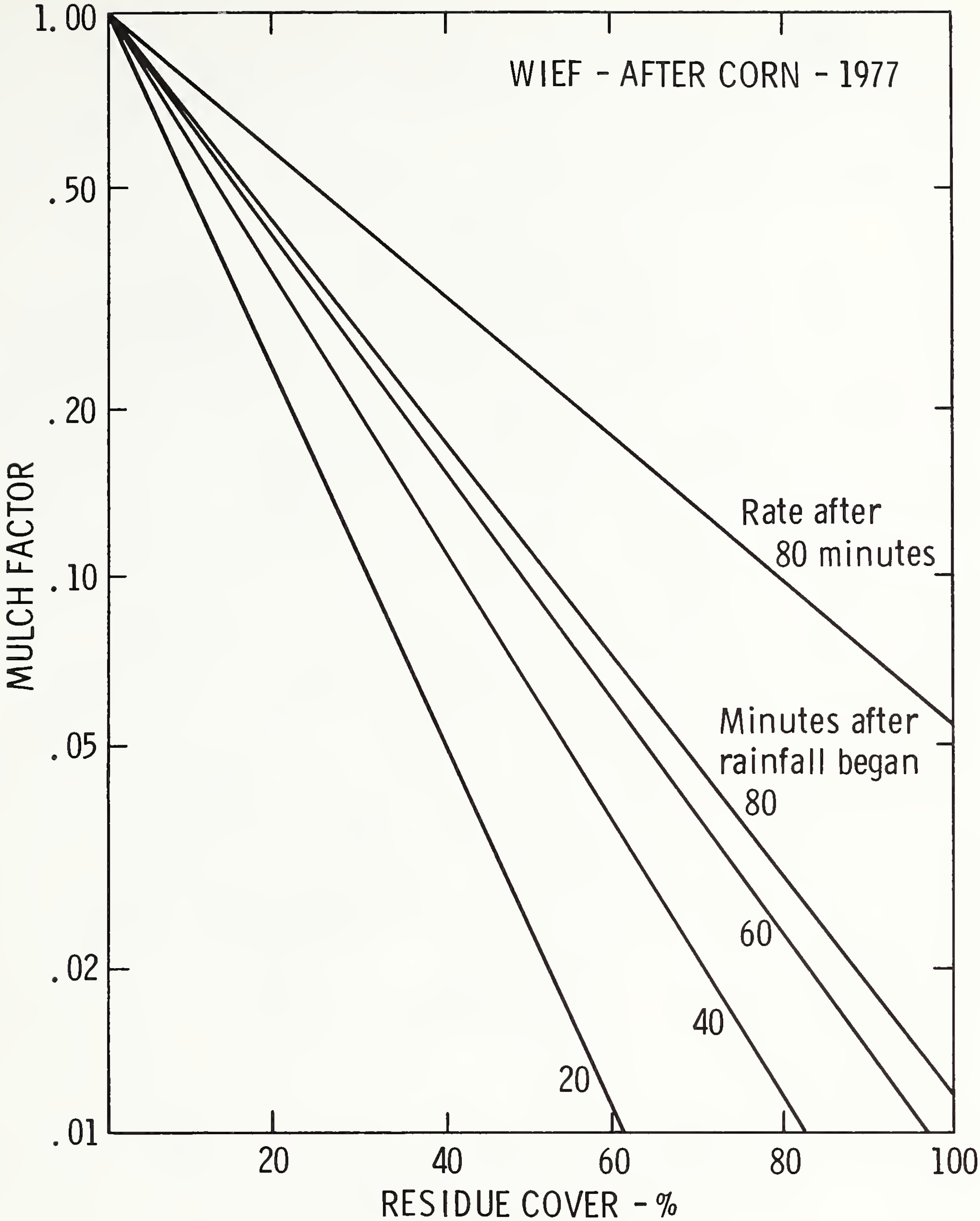


Figure 1. Mulch factor (ratio of erosion with residue cover to erosion without residue cover) vs residue cover for WIEF, 1977.

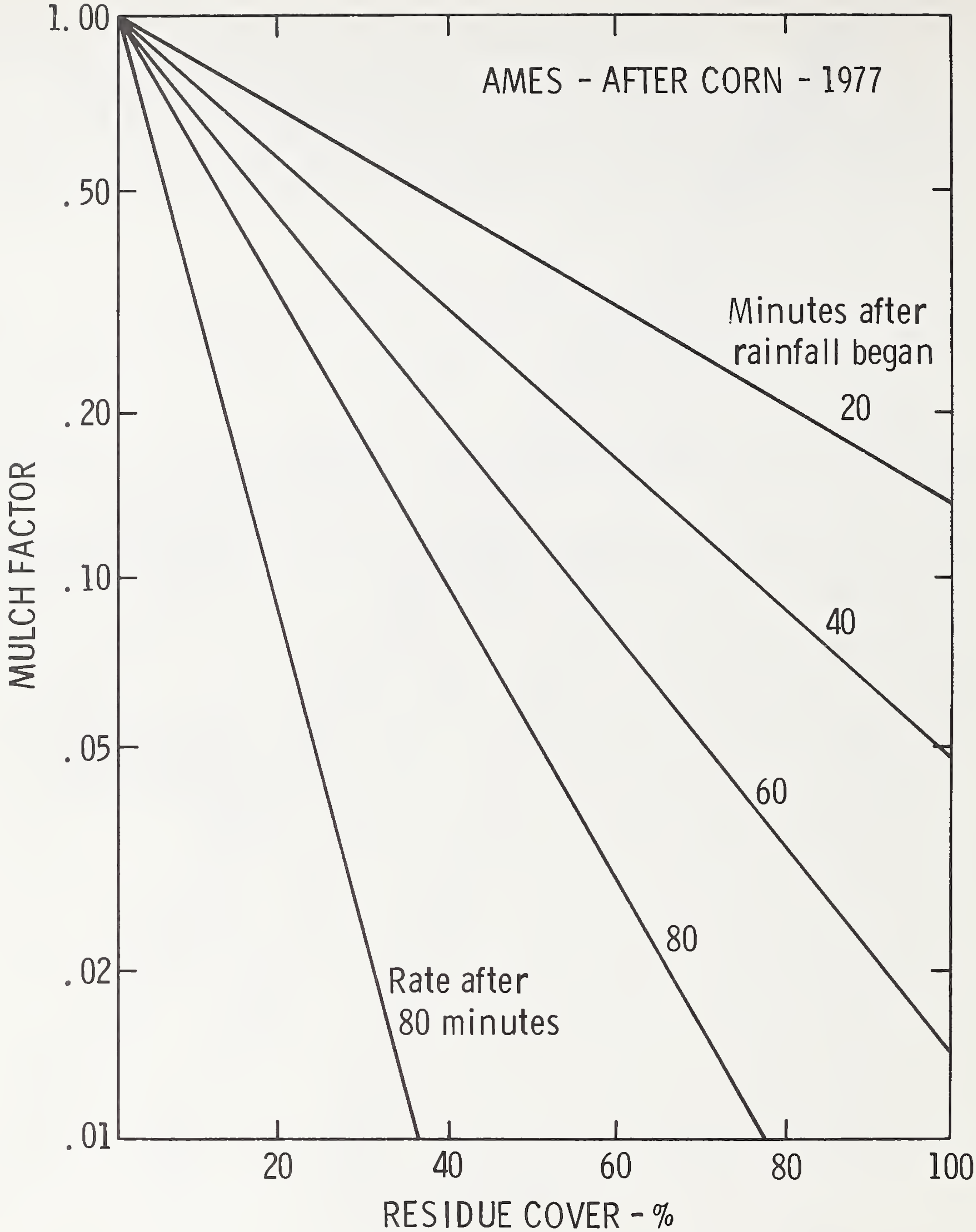


Figure 2. Mulch factor (ratio of erosion with residue cover to erosion without residue cover) vs residue cover Ames, 1977

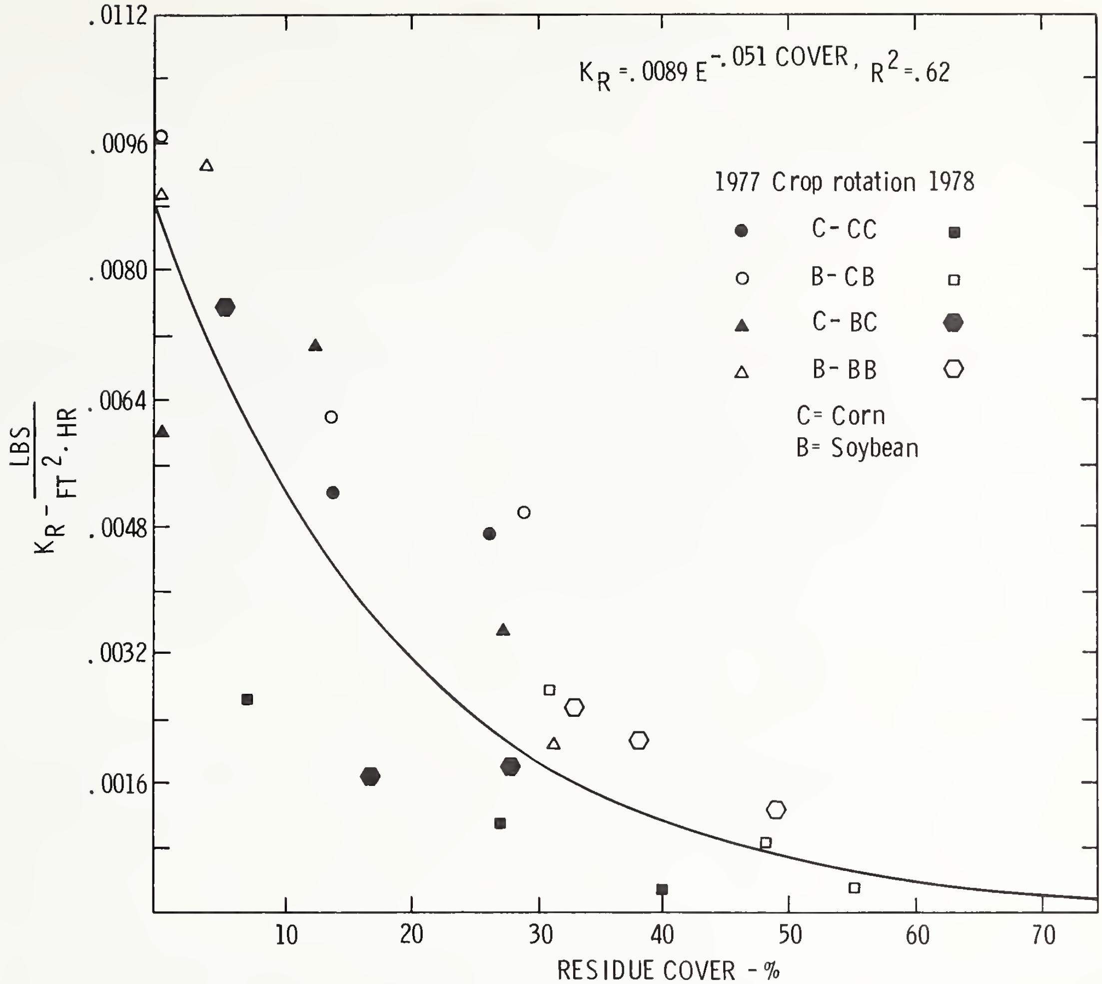


Figure 3. K_R versus residue cover, Western Iowa Experimental Farm.

INTERPRETATION OF RAINFALL SIMULATOR DATA

By Robert A. Young

It is generally agreed, I believe, that rainfall simulators are a useful research tool which have played a valuable role in accumulating data from runoff and erosion studies. However, it is a matter of prime concern just how closely what is happening beneath a rainfall simulator actually relates to what is happening under natural field conditions. Data accumulated with rainfall simulation may be subject to some misinterpretation depending upon the type of simulator used and the conditions under which the tests were made. This is a short discussion on some of the things to watch for and possibly take into consideration when interpreting rainfall simulator data and relating it to natural phenomena.

ADJUSTMENTS TO DATA

A standard design application rate is often used for field studies with rainfall simulators. However, with most simulators it is seldom possible to apply exactly the design intensity each time due to effects of weather, equipment malfunctions, experimental error, etc. Thus, it is usually desirable to adjust the measured runoff and soil loss values to that which would be expected from a standard or design application intensity. The common method of adjustment for runoff has been to assume a constant infiltration rate and subtract the amount of water actually infiltrated during the test from the amount intended to be applied in order to obtain the adjusted runoff amount.

It has been shown, however, that infiltration increases as the application rate increases, even though runoff is occurring (Moldenhauer, et al., 1960, Sloneker and Moldenhauer, 1972). Thus, if an intended application rate is greater than the rate actually applied on a plot, and the standard runoff adjustment is made, the adjusted runoff could be appreciably overestimated. The reverse would be true if the design application rate were less than the actual application rate. For example, on a Barnes loam, if the design intensity were 2.5 iph (6.35 cm/hr) and the applied intensity were only 2.4 iph (6.1 cm/hr), or 4 percent less than the intended rate, which is not uncommon with field rainfall simulators, the adjusted runoff using the standard method of adjustment could be overestimated by about 16 percent. A difference of 8 percent between the design intensity and actual intensity could result in a 27 percent overestimate of the amount of runoff using the standard method of adjustment.

While differences between various treatments subjected to simulated rainfall can usually be compared directly, care must be taken when relating these results to results which would be expected under natural rainfall. One of the most glaring deficiencies with most rainfall simulators, especially

some of the earlier ones, is the lack of a realistic energy output compared to natural rainfall. The single most reliable parameter for relating simulated rainfall characteristics to soil erosion has been the EI factor, or the kinetic energy of the applied rainfall times the maximum 30-minute intensity (Wischmeier, 1959). Energy significantly influences surface sealing and infiltration and subsequent runoff and erosion. Still, relatively few of the many rainfall simulators in existence apply water with a level of energy comparable to that of natural rainfall, and this fact has to be taken into consideration when interpreting data obtained with them.

The EI of a simulator application is proportional to the application intensity squared, assuming the simulator applies rainfall at a constant energy per unit of water and the duration of the simulated storm is 30 minutes or longer. Thus, the usual method of adjusting soil loss data from rainfall simulator tests to those which would be expected from a standard intensity has been to multiply the measured soil loss by the ratio of the intended intensity squared to the actual intensity squared. However, it should be remembered that the drop characteristics of the simulator used have to be determined (size and terminal velocity) and related to the total energy before the results can be related to soil loss or runoff from natural rainfall. A rainulator applies water at only about 78 percent of the energy level of natural rainstorms of similar intensities, and so measured soil losses from simulated storms will be approximately 22 percent less than would be expected from natural rainstorms of equal duration and intensity (Barnett and Dooley, 1972, Young and Burwell, 1972). For other types of rainfall simulators using different nozzles or other types of drop formers, different corrections may be required.

FACTORS AFFECTING RESULTS

Artificial rainfall simulators fall into two main categories, laboratory simulators and outdoor or field plot simulators. Laboratory simulators present certain obvious problems, mainly in soil bed preparation and simulation of natural weather conditions. It is virtually impossible to model a rainstorm. It is also very difficult to move a completely undisturbed soil core from the field into the laboratory, and almost equally difficult to duplicate a field condition in the lab artificially. There are too many soil factors which have to be considered, such as soil moisture content, soil density and degree of compaction, depth of the soil bed, soil particle and aggregate size distribution, aggregate stability, organic matter, and others. It is also difficult to reproduce natural light, temperature, wind, humidity, vegetative cover, microbiological factors, and soil surface conditions. Variations in these parameters from natural conditions have to be considered in interpreting laboratory rainfall simulator results. Outdoor type simulators may have some of these same problems, but usually to a lesser extent.

Laboratory rainfall simulators are also limited in size. Few lab simulators are large enough to study effectively the runoff aspects of the rainfall erosion process. Most of them are used to study, under controlled conditions, those aspects of the erosion process associated with raindrop splash action. To this end they have been used very effectively.

Erosion by runoff, or rill erosion, is more appropriately studied on the larger field plot simulators, such as the rainulator or the rotating boom simulator. Even these are somewhat limited in that most studies must be done with all treatments to be evaluated being applied up and down the slope in order to minimize border effects. Due to the narrow plot width required under most rainfall simulators, tillage treatments other than up and down the slope, will tend to underestimate runoff and soil losses as compared with losses under natural field conditions (Young et al., 1964).

An important factor to take into consideration when interpreting rainfall simulator results is the intermittency of water application necessary with most nozzle type simulators. Nozzles have not yet been developed which are capable of applying realistic drop energy levels and drop characteristics with a low enough flow rate to allow continuous application of water. Consequently, most simulators which apply water at energy levels equivalent to natural rainfall must resort to intermittent application. This has been shown to have a significant effect on the amount of rainfall or energy a soil can absorb before runoff begins (Sloneker and Moldenhauer, 1974, Sloneker et al., 1974). The energy required to initiate runoff increases with the length of time between the intermittent applications of water due to delayed sealing of the soil surface. This effect on surface sealing is due to the fact that soil water pressure varies when subjected to intermittent rainfall. As the water suction increases, the soil shear strength increases and resulting soil splash decreases (Towner and Childs, 1972). Time periods between water application of 10 seconds or greater can cause delayed surface sealing. Rainulators have a 10-second delay between successive water applications at 5 iph intensity, a 20-second delay between applications at 2½ iph intensity, and a 40-second delay at 1¼ iph intensity. This effect may be significant when interpreting results from rainulator tests and comparing them to natural rainfall results.

When interpreting results from outdoor field simulator tests, the possible effect of varying weather conditions should be considered, since tests are apt to be run under a variety of conditions. For example, winds of 20 mph can cause a 5 percent increase in the impact velocity of small raindrops with a subsequent increase in soil loss (Umback, 1966). Winds also increase the angle of impact of striking raindrops. Winds of 20 mph will increase the angle of impacting raindrops 28° in 12 ft of fall. This added to the lateral velocity imparted to the raindrops by the motion of a simulator such as a rainulator can significantly alter the erosion pattern on a test plot.

Temperature may also have an effect on simulator test results. Some field simulators are run at all times of the year. In the north, the testing season usually runs from May to early October. During this period, soil and water temperatures may vary over a wide range. A 50° range of temperatures in Minnesota over the 5-month testing season is not uncommon. Soil temperature can have a significant effect on soil water desorption curves, with the warmer the temperature the less viscous the water and the less water that will be held by the soil. Considering this, it is possible that under high temperatures, the amount of energy and water that will be absorbed by the soil up to initial runoff will be greater than under low temperatures. The actual magnitude of this effect has not been actually measured, but in areas where

there is a wide fluctuation in soil temperatures over the field testing season, it may be worthwhile considering.

Another factor to consider in analyzing rainfall simulator results is the size of the plot and the possible edge effects. The smaller the plot, the larger the edge effects may be and the more significant will be the effect of any anomalies such as worm holes, gopher holes, rocks, etc. A 3-ft square laboratory plot has a plot border to plot area ratio of 1:0.75 while a standard 72.6 ft by 13.3 ft runoff plot has a ratio of 1:5.6. On the other hand, a square 5-acre field will have a ratio of 1:116 and a square 20-acre field will have a ratio of 1:233. Thus, simulator plot results can be significantly affected by edge effects and may give distorted values compared to field situations where edge effects are essentially negligible.

The question of simulator size leads to another major aspect of the interpretation of rainfall simulator data, that of extrapolating results from relatively small rainfall simulator plots to large field size areas. This is probably one of the most neglected areas of erosion research today. It is relatively easy to use a rainfall simulator to study a few parameters at a time to determine their effects on soil loss and runoff while holding all other variables constant. However, the erosion process is extremely complex, affected by an unknown number of variables, and to extrapolate simulator results to a large area where all of these variables will come into play to influence the reactions, is very difficult. The interaction of all these many variables accounts for most of the error in comparing measured soil and water losses from large areas to predicted values calculated from models based on empirical data from small plots and rainfall simulators.

Another feature which cannot easily be simulated with most rainfall simulators and thus, adds to the difficulty of comparing simulator results to natural conditions is the normal variability almost always found in natural rainstorms. Rainfall simulators apply water at constant energy while natural rainfall occurs with continually varying energy and intensities. What effect these varying levels of energy and intensity have on erosion patterns is not really known. Some simulators, such as the rainulator, are capable of applying water at more than one intensity, but none are capable of simulating the wide range of intensities usually found in natural rainstorms. Rainulators have been used to try and match intensity variations in some natural storms with fairly good results (Young and Burwell, 1972), but the storms selected were those whose natural intensity patterns happened to compare favorably with the available intensity range of the rainulator. Few naturally occurring rainstorms do this.

CONCLUSIONS

The factors which I have mentioned are not the only ones that need to be considered in analyzing rainfall simulator data. There are other things to watch for, such as antecedent moisture conditions, return flow, variations in soil erodibility between soils and within a soil over time, etc. There are many others, for each rainfall simulator has its own unique characteristics and limitations which must be considered when analyzing data obtained with it. The points I have mentioned are not meant to detract from the value of the

data obtained with rainfall simulators. The advantages of using rainfall simulators to obtain a large variety of data in a relatively short time and the value of these data usually far outweigh any of the disadvantages or limitations which I have mentioned. The points I have made are simply meant to remind the user of some of the precautions that must be considered when developing conclusions based on data obtained with rainfall simulators and relating them to natural conditions.

REFERENCES

Barnett, A. P. and Dooley, A. E. 1972. Erosion potential of natural and simulated rainfall compared. Trans. ASAE 15(6):1112-1114.

Moldenhauer, W. C., Burrows, W. C. and Swartzendruber, D. 1960. Influence of rainstorm characteristics on infiltration measurements. Int. Congr. Soil Sci. Trans. 7th. (Madison, Wis.) 1:426-432.

Sloneker, L. L. and Moldenhauer, W. C. 1974. Effect of varying the on-off time of rainfall simulator nozzles on surface sealing and intake rate. Soil Sci. Soc. Am. Proc. 38(1):157-158.

Sloneker, L. L., Olson, T. C. and Moldenhauer, W. C. 1974. Soil-water Pressure during intermittent-simulated rain application measured with a new rapid-response tensiometric technique. Soil Sci. Soc. Am. Proc. 38(6):985-987.

Towner, G. D. and Childs, E. C. 1972. The mechanical strength of unsaturated porous granular material. J. Soil Sci. 23:481-498.

Umback, R. C. and Lembke, W. D. 1966. Effects of wind on falling water drops. Trans. ASAE 9(6):805-808.

Wischmeier, W. H. 1959. A rainfall erosion index for a universal soil loss equation. Soil Sci. Soc. Am. Proc. 23(3):246-249.

Young, R. A., Mutchler, C. K. and Wischmeier, W. H. 1964. Influence of row direction and type of vegetal cover on the slope-soil loss relationship. Trans. ASAE 7(3):316, 317 & 320.

Young, R. A. and Burwell, R. E. 1972. Prediction of runoff and erosion from natural rainfall using a rainfall simulator. Soil Sci. Soc. Am. Proc. 36(5):827-830.

AN EXPERIMENT TO COMPARE EROSION AND INFILTRATION FROM VARIOUS SIMULATORS

By John M. Laflen, agricultural engineer[1/]

Prior to the workshop, and before the stringent travel ceilings in FY 79, there was considerable interest in meaningful comparisons of existing rainfall simulators. Questions frequently asked were: What rainfall simulator is best for erosion studies? What simulator is best for infiltration studies? Are erosion estimates valid from small simulators? Are some simulators good for some conditions, but not for others?

Presently, a study has been designed that would make possible valid comparisons of rainfall simulators. Tentatively, as many as 9 simulators are to be compared on 3 soils, 2 plot sizes, and 2 intensities. Hopefully, the study could be completed in 1980.

1/ Science and Education Administration, Agricultural Research, U.S. Department of Agriculture, Ames, IA 50011

ASSESSMENT OF INTENSIVE RANGE PRACTICES ON HYDROLOGIC CHARACTERISTICS USING A MOBILE RAINFALL SIMULATOR, NEVADA AND TEXAS

W. H. Blackburn, range watershed management[1/]

INTRODUCTION

Additional demands being placed on water and the concern of possible nonpoint source pollution from rangelands makes it important that we understand the hydrologic impacts of modern range practices.

High intensity thunderstorms account for most of the runoff and erosion from rangelands. Infiltration and interrill erosion experiments based on sporadic storm events are seldom economically feasible. An experimental alternative to natural precipitation is simulated rainfall applied to small plots. This paper describes research activities using a drip-type rainfall simulator (Blackburn, et al. 1974) on arid and semiarid rangelands of Nevada and Texas.

RAINFALL SIMULATOR APPLICATION

The rainfall simulator has been used to evaluate the influence of intensive range management practices such as livestock grazing systems and brush control on infiltration rates and interrill erosion (Brock, 1978; McGinty, et al. 1978; Wood, et al. 1978; and Wood, 1979). It has also been used to determine the influence of vegetation and soil parameters on infiltration rates and interrill erosion (Brock, 1978; McGinty, et al. 1978; and Wood, 1979).

Studies have also been conducted on Nevada rangelands with the rainfall simulator to assess the impact of prescribed burning, mechanical brush control, seeding, and off-road vehicle use on infiltration rates and interrill erosion. In addition, the influence of vegetation, plant communities and individual plants, and surface soil vesicular horizons on infiltration rates and interrill erosion have been studied (Blackburn, 1973; Blackburn and Skau, 1974; Blackburn, et al. 1974; Blackburn, 1975; Blackburn, et al. 1975; Roundy, et al. 1978; and Eckert, et al. 1979).

The rainfall simulator is presently being used on Texas rangelands to evaluate the impact of livestock grazing systems: continuous grazing with heavy and moderately stocked pastures; four-pasture, three-herd deferred-rotation grazing; and short duration grazing. The impact of prescribed

---

1/ Associate professor of watershed management, Range Science Department, Texas A&M University, College Station, Texas 77843.

burning, chemical and mechanical brush control on infiltration rates and interrill erosion are also being investigated.

When using a rainfall simulator to evaluate management practices, close attention must be given to soil and vegetation differences on the site. Stratified sampling should be employed when such differences occur to minimize within treatment variation. For example, three plant communities occurring in a mosaic pattern on a Leeray clay soil series in the Rolling Plains of Texas exhibited significantly different infiltration rates (Table 1). Infiltration rates after 30 minutes were highest in the mesquite zonal community and lowest in the sodgrass community with the bunchgrass community values being intermediate.

Table 1.--Infiltration rates after 30 minutes for the mesquite zonal, bunchgrass and sodgrass communities with the soil initially at field capacity.

Plant Community	Infiltration Rate (cm/hr)
Mesquite zonal	15.2
Bunchgrass	11.7
Sodgrass	6.5

LITERATURE CITED

(1) Blackburn, W. H.
1973. Infiltration rate and sediment production of selected plant communities and soils in five rangeland watersheds in Nevada. Nev. Agr. Exp. Sta., Univ. of Nev. (Reno). R-92:99 p.

(2) Blackburn, W. H.
1975. Factors influencing infiltration and sediment production of semiarid rangelands, Nevada. Water Resour. Res. 11(6):929-927.

(3) Blackburn, W. H. and C. M. Skau
1974. Infiltration rates and sediment production of selected plant communities and soils of Nevada. J. Range Manage. 27:476-480.

(4) Blackburn, W. H., R. E. Eckert, Jr., M. K. Wood and F. F. Peterson
1975. Influence of Vesicular Horizons on Watershed Management. In: Proceedings of Watershed Management, A Symposium. Irrigation and Drainage Div. Amer. Soc. Civil Eng., Logan, Utah. August 11-13.

(5) Blackburn, W. H., R. O. Meeuwig and C. M. Skau
1974. A mobile infiltrometer for use on rangelands. J. Range Manage. 27:322-323.

(6) Brock, J. H.
1978. Influence of honey mesquite and its control on zonal vegetation patterns. Ph.D. Diss., Range Sci. Dep., Texas A&M Univ., College Station. 201 p.

(7) Eckert, R. E., Jr., M. K. Wood, W. H. Blackburn and F. F. Peterson
1979. Impacts of off-road vehicle traffic on infiltration rates and sediment production of some desert soils. J. Range Manage. 33. (In press).

(8) McGinty, W. A., F. E. Smeins and L. B. Merrill
1978. Influence of soil, vegetation and grazing management on infiltration rate and sediment production of Edwards Plateau rangeland. J. Range Manage. 32:33-37.

(9) Roundy, B. A., W. H. Blackburn and R. E. Eckert, Jr
1978. Influence of prescribed burning on infiltration and sediment production in the pinyon-juniper woodland, Nevada. J. Range Manage. 31:250-253.

(10) Wood, M. K.
1979. Grazing systems influence on infiltration rate and sediment production in the Rolling Plains of Texas. Ph.D. Diss., Range Sci. Dep., Texas A&M Univ., College Station. 117 p.

(11) Wood, M. K., W. H. Blackburn, F. E. Smeins and W. A. McGinty
1978. Hydrologic impacts of grazing systems. Proc. Internat. Rangeland Cong. Soc. Range Manage.

NEVADA RANGELAND HYDROLOGY STUDIES

J. C. Brown, Research Associate[1]

The University of Nevada Reno is currently involved in two research programs designed to assess the effects of grazing management systems and range improvement practices on watershed hydrology and water quality. Due to the infrequency of natural rainfall-runoff events, it is expected that rainfall simulation will play a major role as an evaluation tool. The purpose of this paper is to briefly describe these two projects and proposed rainfall simulation activities.

1. <u>Gund Ranch</u>

The Gund Ranch is located in Grass Valley, 40 miles northeast of Austin, in the central part of the State. Despite the name, the area basically consists of a large playa or dry lake flanked by sagebrush-covered alluvial fans and steep rocky mountains. Annual precipitation here is 8-12 in., occurring mostly as snow in winter. On the alluvial fan areas, a number of range improvement treatments including spraying, burning, and reseeding are contemplated. Hydrology objectives are generally to assess the probable effects of these treatments on runoff and sediment yields.

Since natural surface runoff events may require a 5-, 10-, 20-, or even 50-year storm, rainfall simulation techniques are the only practical way to approach the study objectives. Various treatments here will be confined to 40-acre plots. Replicated simulator runs with measurements of infiltration capacity, runoff volumes, and sediment yields will be made on each plot before treatment and at various times after treatment. In this manner, we hope to assess site and antecedent moisture variability as well as long-term post treatment trends.

2. <u>Saval Ranch</u>

The Saval Ranch is located 30 miles north of Elko in northeastern Nevada. The study area encompasses 3 major watersheds with perennial or near-perennial streamflow. Headwater areas are mountainous but not steep, and are covered primarily with sagebrush, bitterbrush, and some patches of aspen. Lowland areas consist of a rather flat bench dissected by the main streams and a number of ephemeral channels. These lowlands provide an excellent opportunity for watershed research; the watersheds of streams running through them are 4 to 6 miles long but

[1] University of Nevada Reno

only a few hundred yards to ¼-mile wide. This allows the possibility of division into subwatersheds with long stream reaches but small contributing areas; integrity of drainage for treatment areas can be maintained on relatively small parcels of land.

The general hydrology objective of this project is to evaluate the effects of grazing management on runoff and water quality. Specifically, the current season-long grazing system will be converted to a 5 pasture rest-rotation system in 2-3 years. The effects of this change in management, comparisons with no-grazing controls, and other tests involving grazing intensities are contemplated during the 10-15 year life of the study.

The tentative approach to these objectives involves fitting a simulation model to the hydrologic systems operating here. It is hoped that by using rainfall simulation on the hill slopes and water quality and runoff data from the streams the model can be fitted and validated. Changes in value of model parameters, then, can be attributed to changes in management.

INVENTORY OF RAINFALL SIMULATORS

G. D. Bubenzer[1]

Rainfall simulators have been used for the past half century to assist researchers in their attempts to understand the erosion, runoff and infiltration processes. During this period several different types of simulators have evolved. This inventory was prepared to assist in comparing the rainfall characteristics of simulators used in recent years. The simulators have been divided into two groups. The first group, described in Table 1, includes simulators which produce rainfall by means of a nozzle. The second category of rainfall simulators, Table 2, includes those which use drop formers to produce rainfall.

Several different nozzles with widely varying drop characteristics have been used on modern rainfall simulators. From this group four nozzles seem to predominate. The Spray Engineering Company's 7LA nozzle was first used on the Purdue Sprinkling Infiltrometer (Bertrand and Parr, 1961). Several variations of this infiltrometer are currently in use. Amerman et al. (1970) and Rawitz et al. (1972) described slotted rotating disk units for the Purdue Infiltrometer to reduce rainfall intensity. Dixon and Peterson (1969) developed a vacuum system for accumulating the runoff from the plot. There have been no major changes in the nozzle.

The Rainulator (Meyer and McCune, 1958) used the Spraying Systems 80100 Veejet nozzle. The nozzle was selected because it closely approximated the drop size distribution of erosive storms in the midwest. The Rainulator has also been modified to meet special research needs. Seimens and Oschwald (1978) constructed a self-propelled unit. Swanson (1965) used the same nozzle on a trailer mounted, rotating boom simulator. Bubenzer and Meyer (1965) also used the 80100 Veejet nozzle to develop an oscillating laboratory simulator. The oscillating simulator greatly reduced the period of intermittency of the Rainulator. The oscillating nozzle concept has also been incorporated into the inter-rill simulator (Meyer and Harmon, 1977) and the new Raunulator currently being developed by Foster. The inter-rill simulator and the new Rainulator use the 80150 Veejet nozzle as well ad the 80100 Veejet. The drop size distribution and the kinetic energy level obtained with the 80150 Veejet are somewhat greater than those for the 80100.

Holland (1969) used the Rainjet 78C nozzle on a large plot simulator. Lusby (1977) modified this simulator for field work. The primary advantages

[1]/Associate Professor, Agricultural Engineering Department, University of Wisconsin - Madison.

of the simulator are the ease of assembly and the flexibility of plot size and shape. Drop sizes and energy levels are, however, lower than those simulators using the Veejet 80100 and 80150 nozzles.

The Spraying Systems 1.5H30 Fulljet nozzle has also been used on several simulators. This nozzle is used in connection with the rotating disk (Morin, 1967) to reduce rainfall intensity. The median drop size of 2.6 mm compares well with erosive natural storms.

Several other nozzles are described in Table 1. Included in this group is the Type F nozzle described by Wilm (1953), Dortignac (1951), and Packer (1957). Drop sizes from the Type F nozzle are large, however, the kinetic energy is low due to the short fall height. The Spraying Systems 14WSQ Fulljet nozzle is being used on the Palouse Infiltrometer to simulate the small drop size and low intensity events of the Pacific Northwest. The Beta Fog SRN 303 nozzle, used by Shriner (1977) on the RAINS simulator, also produces a drop size much less than those of natural rainfall.

The second group of rainfall simulators included in the inventory are those using drop formers to produce rainfall (Table 2). Early simulators used small pieces of yarn to form drops. Recent simulators have used glass capillary tubes, hypodermic needles, polyethylene tubing, and brass or stainless tubes as drop formers. Reported drop diameters range from 2.2 mm (Bubenzer and Jones, 1971) to 5.6 mm (Adams et al. 1957). Most simulators produce drops at a constant size for a given rainfall module. Brakensiek et al. (1979) used compressed air blowing around the drop formers to produce drops of varying sizes from the same module. Most of the simulators described in Table 2 cover relatively small plots. The most notable exceptions are the simulators developed by Chow and Harbaugh (1965) and Peterson (1977) and the laboratory simulators located at Purdue University and Utah State University.

Pertinent references are given in the right hand column of Tables 1 and 2. These references describe in greater detail the drop characteristics, construction details, and operation of the various simulators.

Table 1. Rainfall Simulators and Infiltrometers Using Nozzles to Simulate Rainfall

Rainfall Simulator Location	Nozzle	Pressure (KPa)	Nozzle Movement and Spray Pattern	Drop Size (mm) D_{10}	D_{50}	D_{90}	Intensity (mm/hr)	Plot Size per Unit (m x m)	Use	Reference
Rainulalator USDA - SEA - AR Lafayette, Indiana	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.1	3.0	64 & 127	4 x 11.5	Erosion	Meyer, 1958 Hermsmeier, 1963
Rainulator USDA - SEA - AR Watkinsville, Georgia	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.1	3.0	64 & 127	4 x 11.5	Erosion	Hermsmeier, 1963
Rainulator USDA - SEA - AR Morris, Minnesota	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.1	3.0	64 & 127	4 x 11.5	Erosion Infiltration	Hermsmeier, 1963
Rainulator Univ. of Illinois Urbana, Illinois	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.1	3.0	64 & 127	4 x 11.5	Erosion	Seimens, 1978
Rainulator Dept. of Prim. Ind. Toowooba, Queensland Australia	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.2	3.2	30 - 200	4 x 22.5	Erosion Infiltraion	McKay, 1978
Modified Rainulator New Mexico State Univ. Las Cruces, New Mexico	Spraying Systems 80100 Veejet	41.4	Lateral Intermittent	1.0	2.1	3.0	101 & 203	5.0 x 6.5	Erosion	Anderson, 1968
New Rainulator USDA - SEA - AR Lafayette, Indiana	Spraying Systems 80100 Veejet 80150 Veejet	41.4	Oscillating Intermittent	1.0 1.1	2.1 2.5	3.2 4.2	2 - 127	4 x 11.5	Erosion Infiltration Runoff	
Rotating Boom USDA - SEA - AR Lincoln, Nebraska	Spraying Systems 80100 Veejet	41.4	Rotating Intermittent	1.0	2.1	3.0	64 & 127	4 x 11	Erosion Infiltration	Swanson, 1965
Rotating Boom USDA - SEA - AR Ames, Iowa	Spraying Systems 80100 Veejet	41.4	Rotating Intermittent	1.0	2.1	3.0	64 & 127	4 x 11	Erosion	Swanson, 1965
Laboratory Simulator USDA - SEA - AR Lafayette, Indiana	Spraying Systems 80100 Veejet	41.4	Oscillating Intermittent	1.0	2.1	3.0	38	0.7 x 3.3	Erosion	Bubenzer, 1965
Laboratory Simulator Univ. of Wisconsin Madison, Wisconsin	Spraying Systems 80100 Veejet	41.4	Oscillating Intermittent	1.0	2.1	3.0	38	1 x 5	Erosion Runoff	Bubenzer, 1965
Inter-rill Simulator USDA - SEA - AR Oxford, Mississippi	Spraying Systems 80100 Veejet 80150 Veejet	41.4	Oscillating Intermittent	0.7 1.1	1.6 2.5	3.2 4.2	10 - 127	0.7 x 0.9	Erosion	Meyer, 1979
Inter-rill Simulator Michigan Tech Univ. Houghton-Hancock, Michigan	Spraying Systems 80100 Veejet 80150 Veejet	41.4	Oscillating Intermittent	0.7 1.1	1.6 2.5	3.2 4.2	10 - 127	0.7 x 0.9		Meyer, 1979

Table 1. Rainfall Simulators and Infiltrometers Using Nozzles to Simulate Rainfall - Continued

Rainfall Simulator Location	Nozzle	Pressure (KPa)	Nozzle Movement and Spray Pattern	Drop Size (mm) D_{10}	D_{50}	D_{90}	Intensity (mm/hr)	Plot Size per Unit (m x m)	Use	Reference
Rainfall Simulator Australia	Spraying Systems 8070 Veejet	41.4	Lateral Intermittent					4.6 x 4.6	Erosion	Turner, 1969
Palouse Field Station USDA - SEA - AR Pullman, Washington			Stationary Continuous				2 - 2000	2.6 x 13.1	Erosion	
Palouse Infiltrometer Univ. of Idaho Moscow, Idaho	Spraying Systems 14WSQ Fulljet	41.4	Stationary Intermittent	0.8	1.7	2.6	1 - 50	2 x 2	Infiltration	
Purdue Sprinkling Infiltrometer Purdue University Lafayette, Indiana	Spray Engr Co 7LA 5B 5D	41.4	Stationary Continuous	0.1 0.1 0.1	1.2 0.8 0.6	2.4 1.5 1.5	119 64 82	1.2 x 1.2	Infiltration	Bertrand, 1961
Modified Purdue Type Univ. of Wisconsin Madison, Wisconsin	Spray Engr Co 7LA	41.4	Stationary Intermittent	0.1	1.2	2.4	2 - 111		Infiltration Nut. Transp.	Dixon, 1964 Amerman, 1970
Modified Purdue Type USDA - SEA - AR Tuscon, Arizona	Spray Engr Co 7LA	41.4	Stationary Continuous	0.1	1.2	2.4	119	1.0 x 1.0	Infiltration Erosion Soil Mgt.	Dixon, 1968
Modified Purdue Type Univ. of Missouri Columbia, Missouri	Spray Engr Co 7LA	41.4	Stationary Intermittent	0.1	1.2	2.4	2 - 111			
Modified Purdue Type USDA - SEA - AR Columbia, Missouri	Spray Engr Co 7LA	41.4	Stationary Intermittent	0.1	1.2	2.4	2 - 111			
Variable Intensity Inf. Hebrew Univ. Rehovot, Israel	Spray Engr Co 7LA	41.4	Stationary Intermittent	0.1	1.2	2.4	2 - 111	1.2 x 1.2	Infiltration	Rawitz, 1972
RFER Colorado State Univ. Fort Collins, Colorado	Rainjet 78C	193	Stationary Continuous	0.5	1.2	3.0	12 - 100		Runoff	Holland, 1969
Sprinkler Head Grid North Dakota State Univ. Mandan, North Dakota	Rainjet 78C	193	Stationary Continuous	0.7	1.4	2.8	36 & 58	13 x 26	Erosion Infiltration	Holland, 1969
USGS USGS Lakewood, Colorado	Rainjet 78C	193	Stationary Continuous	0.6	1.4	2.8	50		Erosion Infiltration Runoff	Lusby, 1977
USGS Bur of Land Mgt Denver, Colorado	Rainjet 78C	193	Stationary Continuous	0.6	1.4	2.8	50		Erosion Infiltration	Lusby, 1977
USGS USDA - SEA - AR Tuscon, Arizona	Rainjet 78C	193	Stationary Continuous	0.6	1.4	2.8	50		Erosion Infiltration	Lusby, 1977

Table 1. Rainfall Simulators and Infiltrometers Using Nozzles to Simulate Rainfall - Continued

Rainfall Simulator Location	Nozzle	Pressure (KPa)	Nozzle Movement and Spray Pattern	Drop Size (mm) D_{10}	D_{50}	D_{90}	Intensity (mm/hr)	Plot Size per Unit (m x m)	Use	Reference
USGS USDA - SEA - AR Sidney, Montana	Rainjet 78C	207	Stationary Continuous	0.7	1.5	2.4	64		Erosion Infiltration	Lusby, 1977
Rotating Disk Simulator Soil Erosion Res. Sta. Emek, Hefer Israel	Spraying Systems 1HH12 Fulljet 1.5 H30 Fulljet	60	Stationary Intermittent				9 - 74 15 - 143	1.0 x 1.5	Erosion	Morin, 1967
Rotadisk Rainulator Univ. of Arizona Tuscon, Arizona	Spraying Systems 1.5 H30 Fulljet		Stationary Intermittent				17 - 1520	1.5 x 1.5	Erosion Infiltration	Cluff, 1971
Morin and Goldberg Type Gunnedah Soil Cons Res Ctr Gunnedah, Australia	Spraying Systems 1.5 H30 Fulljet	70	Stationary Intermittent	1.9	2.6	4.3	58 - 115	1.0 x 1.5	Erosion	Marston, 1978
Waite Institute Waite Agr Res Inst South Australia	Spraying Systems 1.5 H30 Fulljet	69	Stationary Intermittent		2.4		10 - 150	1.0 x 1.0	Erosion	Grierson, 1975
Rainfall Simulator Cornell University Ithaca, New York	Spraying Systems 7309 Flat Teejet 8015 Flat Teejet	137 - 275	Rotating Intermittent				17 - 282		Pest. Move.	Brockman, 1975
Portable Simulator Commonwealth Atherton, Queensland Australia	Rose Sprayhead		Lateral Intermittent		1.3		80	2.0 x 3.3	Erosion Infiltration Nut. Move.	Costin, 1970
Raintower USDA - SEA - AR Manhattan, Kansas	Spraying Systems 14WSQ & 35WSQ		Stationary Continuous	1.0	2.1	3.9	18	1.5 x 31.	Erosion	Lyles, 1969
Laboratory Simulator Univ. of Salford Lancashire, U.K.	Childs (PVC)	45	Stationary				0 - 300	6.2 x 4.1	Infiltration Runoff	Nassif, 1975
RAINS Oak Ridge National Lab Oak Ridge, Tennessee	Beta Fog SRN303		Stationary Continuous	0.4		1.2	5 - 27	1.0 x 1.0	Infiltration Nut. Transp.	Shriner, 1977
Type F Infiltrometer USDA - SEA - AR Beltsville, Maryland	Type F	193 - 248	Stationary Continuous				46 - 64	2.0 x 3.9	Erosion Infiltration	Wilm, 1943
Rocky Mountain Infilt. USDA - Forest Service Ft. Colorado	Type F	138 - 206	Stationary Continuous				127	0.3 x 0.8	Erosion Infiltration Runoff	Dortignac, 1951
Intermountain Infilt. USDA - Forest Service Ogden, Utah	Type F	241	Stationary Continuous				25 - 152	0.6 x 1.8	Erosion Infiltration Runoff	Packer, 1957
Rocky Mountain Infilt. Utah State University Logan, Utah	Type F	138 - 206	Stationary Continuous				127	0.5 x 0.7	Erosion Infiltration	Meeuwig, 1969

Table 2. Rainfall Simulators and Infiltrometers Using Drop Formers to Simulate Rainfall

Rainfall Simulator Location	Drop Formers	Fall Distance (m)	Drop Size (mm)	Intensity (mm/hr)	Plot Size (mxm) or (m^2)	Use	Reference
Mobile Infiltrometer Univ. of Wyoming Laramie Wyoming	Yarn	2.6		25 - 152	0.6 x 0.6	Infiltration Runoff	Barnes, 1957
Portable Infiltrometer Iowa State Univ. Ames, Iowa	Glass Capillary Tubes	1.0	5.6	101	Circular 0.017 m^2	Erosion Infiltration Runoff	Adams, 1957
Laboratory Simulator Univ. of Maine Orono, Maine	Stainless Tubes	7.2	3.2 5.1	38 - 50	Circular 1.33 m^2	Erosion	Mutchler, 1963 Epstein, 1966
Laboratory Simulator Univ. of Illinois Urbana, Illinois	Polyethylene Tubes	2.7	3.2	19 - 33	12 x 12	Runoff	Chow, 1965 Chow, 1974
Low Intensity Simulator Nat'l & Univ. Instit. of Agr. Rehovot, Israel	Stainless Tubes		2.8	6	0.5 x 0.5	Infiltration	Steinhardt, 1966
Drop Tower Simulator Univ. of Illinois Urbana, Illinois	Hypodermic Needles Polyethylene Tubes Stainless Tubes	8.9	2.2 3.4 4.9	10 - 70 45 - 350 100 - 525	1.3 x 1.3	Erosion Surfsce Storage	Bubenzer, 1971
Mobile Infiltrometer Texas A & M Univ. College Station, Texas	Stainless Tubes	2.3	2.5	5 - 250	1.0 x 1.0	Erosion Infiltration	Blackburn, 1974
Laboratory Simulator Purdue University Lafayette, Indiana	Polyethylene Tubes	2.6	2.7	13 - 200	4.6 x 4.6	Runoff	
Laboratory Simulator USDA - SEA - AR Oxford, Mississippi	Hypodermic Needles	6.7	Variable	1 - 250	Circular 0.45 m^2	Erosion Infiltration	Römkens, 1975
Tahoe Basin Simulator Univ. of California Davis, California	Polyethylene Tubes	2.5	3.2	76 - 250	0.6 x 0.6	Erosion Infiltration	Munn, 1976
Laboratory Simulator CSIRO - Div. of Soils Canberra, Australia	Hypodermic Needles	12.3	2.5 5.1	20 - 250	0.6 x 3.0	Erosion	Walker, 1977
Laboratory Simulator Utah State Univ. Logan, Utah	Brass Tubes	5.0	4.5	25 - 787	9.8 x 9.8	Erosion Runoff	
Portable Simulator Utah State Univ. Logan, Utah	Hypodermic Needles	1.6	2.5	38 - 250	0.6 x 0.6	Erosion Infiltration Chemical Transp.	Malkuti, 1978

Table 2. Rainfall Simulators and Infiltrometers Using Drop Formers to Simulate Rainfall - Continued

Rainfall Simulator Location	Drop Formers	Fall Distance (m)	Drop Size (mm)	Intensity (mm/hr)	Plot Size (mxm) or (m^2)	Use	Reference
Drip Infiltrometer USDA - SEA - AR Coshocton, Ohio	Hypodermic Needles	2.6	Variable	5 - 102	1.0 x 2.0	Infiltration	Brakensiek, 1979
Laboratory Simulator Univ. of Nebraska Lincoln, Nebraska	Plastic Rods	11.3	5.1	20 - 120	Circular $.005m^2$	Erosion	Mazurak, 1968
Laboratory Simulator USDA - SEA - AR Fort Collins, Colorado	Teflon Tubing	3.0	3.6	76 - 203	1.2 x 12	Erosion	Peterson, 1977
Laboratory Simulator State Univ. Coll. of Forestry Syracuse, New York	Polyethylene Tubes	1.0	3.2	19 - 33	0.7 x 0.7	Runoff	Black, 1970
Laboratory Simulator State Univ. Coll. of Foestry Syracuse, New York	Polyethylene Tubes	1.0	3.2	19 - 33	2.0 x 2.0	Runoff	Black, 1972
Laboratory Simulator State Univ. of Ghent Ghent, Belgium	Copper Tubes	2.8	Varied	4.7-64.5		Erosion	Gabriels, 1975
Laboratory Simulator CSIRO Canberra, Australia	Hypodermic needles Plastic Tubea	11.2	3.8 5.1	0 - 300	1.0 x 1.0	Erosion	Kinnell, 1974
Laboratory Simulator Uganda		6.0	3.2 6.2	50 - 152		Erosion	Rose, 1960
Portable Simulator New Zealand	Wire			20 - 300	Circular $0.015m^2$	Infiltration	Selby, 1970

REFERENCES

Adams, J. E., D. Kirkham and P. P. Nielsen. 1957. A portable rainfall Simulator infiltrometer and physical measurements of soil in place. Soil Sci. Soc. Amer. Proc. 21:473-477.

Amerman, C. R., D. I. Hillel and A. E. Peterson. 1970. A variable intensity sprinkling infiltrometer. Soil Sci. Soc. Amer. Proc. 34(5):830-832.

Anderson, J. U., A. E. Stewart and P. C. Gregory. 1968. A portable rainfall simulator and runoff sampler. New Mexico State Univ. Ag. Expt. Sta. Rept 143, Las Cruces 5 p.

Barnes. O. F., and G. Costel. 1957. A mobile infiltrometer. Agron. J. 49:105-107.

Bertrand, A. R., and J. F. Parr. 1961. Design and operation of the Purdue sprinkling infiltrometer. Purdue Univ. Res. Bull. No. 723. Lafayette, Ind.

Black, P. E. 1970. Runoff from watershed models. Water Resources Res. 6(2):465-477.

Black, P. E. 1972. Hydrograph responses to geomorphic model watershed characteristics and precipitation variables. J of Hydrology. 17:309-329.

Blackburn, W. H., R. O. Meeuwig and C. M. Skau. 1974. A mobile infiltrometer for use on rangeland. J. of Range Management 27(4):322-323.

Brakensiek, P. O., W. J. Rawls, and W. R. Hamon. 1979. Application of an infiltrometer system for describing infiltration into soils. Trans of ASAE (in press).

Brockman, F. E., W. B. Duke, and J. F. Hunt. 1975. A rainfall simulator for pesticide leaching studies. Weed Sci. 23(6):533-535.

Bubenzer, G. D., and B. A. Jones, Jr. 1971. Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Trans of ASAE 14(4):625-628.

Bubenzer, G. D., and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans of ASAE 8:73 and 75.

Chow, V. T., and T. E. Harbaugh. 1965. Raindrop production for laboratory watershed experimentation. J. Geophys. Res. 70(24):6111-6119.

Chow, V. T., and B. C. Yen. 1974. A laboratory watershed experimentation system. Hydr. Engr. Series No. 27. Civil Engineering Dept., Univ. of Illinois. Urbana. 196 p.

Cluff, C. B., 1971. The use of a realistic rainfall simulator to determine relative infiltration rates of contributing watershed to the Lower Gila below Point Rock Dam. Univ of Ari., Water Res Center. Tuscon

Costin, A. B., and D. A. Gilmour. 1970. Portable rainfall simulator and plot unit for use in field studies of infiltration, runoff, and erosion. J. Appl. Ecol. 7(1):193-200.

Dixon, R. M., and A. E. Peterson. 1964. Construction and operation of a modified spray infiltrometer. Univ. of Wis. Res. Rep. 15, Madison. 31 p.

Dixon, R. M., and A. E. Peterson. 1968. A vacuum system for accumulating runoff from infiltrometers. Soil Sci. Soc. Amer Proc. 32(1):123-125.

Dortignac, E. J. 1951. Design and operation of Rocky Mountain Infiltrometer. Station Paper No. 5, USDA Forest Service, Rock Mountain Forest Range Experiment Station, Ft. Collins, Colorado.

Epstein, E., and W. J. Grant. 1966. Design construction and calibration of a laboratory rainfall simulator. Univ. of Maine Tech. Bull. 22. Orono.

Gabriels, D., and M. DeBoodt. 1975. A rainfall simulator for erosion studies in the laboratory. Pedologie 25(2):80-86.

Grierson, I. T. 1975. The effect of gypsum on the chemical and physical properties of a range of red brown earths. Unpublished M. Agr. Sci. Thesis. Univ. of Adelaide. South Australia.

Hermseier, L. F., L. D. Meyer, A. P. Barnett and R. A. Young. 1963. Construction and operation of a 16-unit Rainulator. ARS 41-62.

Holland, M. E. 1969. Design and testing of a rainfall system. Col State Univ. Exp. Sta. CER 69-70 MEH 21. Ft. Collins

Kinnell, P. I. A. 1974. Splash erosion: Some observations on the splash cup technique. Soil Sci. Soc. Am. Proc. 38(4):657-660.

Lusby, G. C. 1977. Determination of runoff and sediment by rainfall simulation. In erosion: research techniques, erodibility and sediment delivery. Geo. Abstracts Ltd., Norwich, England.

Lyles, Leon, L. A. Disrud and W. P. Woodruff. 1969. Effects of soil physical properties, rainfall characteristics and wind velocity on clod disintegration by simulated rainfall. Soil Sci. Amer. Proc. 33(2):302-306.

Malekuti, A., and G. F. Gifford. 1978. Natural vegetation as a source of diffuse salt within the Colorado River Basin. Water Res. Bull. 14:195-205.

Marston, D. 1978. The use of simulated rainfall in assessing the erodibility of various stubble management practices. Proc. Conf. on Agr. Engr. in 1978. Toowomba, Australia.

Mazurak, A. O., and P. N. Mosher, 1968. Detachment of soil particles in simulated rainfall. Soil Sci. Soc. Am. Proc. 32:716-719.

McKay, M. E. and R. J. Loch. 1978. A modified Meyer rainfall simulator. Proc. Conf. on Agr. Engr. in 1978. Toowomba, Australia. pp 78-81.

Meeuwig, R. O. 1969. Infiltration and soil erosion as influenced by vegetation and soil in northern Utah. J. Range Mgt. 23(3):185-188.

Meyer, L. D., and W. C. Harmon. 1979. Rainfall simulator for evaluating erosion rates and sediment sizes for row sideslopes. Trans ASAE 22(1):100-103.

Meyer, L. D., and D. L. McCune. 1958. Rainfall simulator for runoff plots. Ag. Engr 39(10):644-648.

Morin, J., D. Goldberg and I. Seginer. 1967. A rainfall simulator with a rotating disk. Trans. ASAE 10:74-77.

Munn, J. R., and G. L. Huntington. 1976. A portable simulator for erodibility and infiltration measurements on rugged terrain. Soil Sci. Soc. Amer. J. 40(4):622-624.

Mutchler, C. H. and W. C. Moldenhauer. 1963. Applicator for laboratory rainfall simulator. Trans. ASAE 6(3):220-222.

Nassif, S. H., and E. M. Wilson. 1975. The influence of slope and rain intensity on runoff and infiltration. Hydrological Sci. - Bull. XX, 4-12.

Packer, Paul E. 1957. Intermountain infiltrometer. Misc. Publ. No. 14. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Peterson, R. J. 1977. Laboratory simulation of soil erosion. Unpublished MS thesis. Colorado State Univ. Ft. Collins. 70 p.

Rauzi, F., and A. W. Zingg. 1956. Rainmaker helps prove a theory. Soil Cons. 21(10):228.

Rawitz, E., M. Margolin, and D. I. Hillel. 1972. An improved variable-intensity sprinkling infiltrometer. Soil Sci. Soc. Amer. Proc. 36(3):533-535.

Romkens, M. J. M., L. F. Glenn and D. W. Nelson. 1975. A laboratory rainfall simulator for infiltration and soil detachment studies. Soil Sci. Soc. Amer. Proc. 39(1):158-160.

Rose, C. W. 1960. Soil detachment caused by rainfall. Soil Science 89:28-35.

Seimens, J. C., and W. R. Oschwald. 1978. Corn-soybeans tillage systems: erosion control, effects on crop production, costs. Trans ASAE 21(2):293-302.

Selby, M. J. 1970. Design of a hand-portable rainfall simulating infiltrometer, with trial results from the Otutira catchment. J. Hydrology 9(2):117-132.

Shriner, D. S., C. H. Abner and L. K. Mann. 1977. Rainfall simulation for environmental application. Oak Ridge National Lab. Env. Sci. Div. Pub. No. 1067.

Steinhardt, R., and D. I. Hillel. 1966. A portable low-intensity rain simulator for field and laboratory use. Soil Sci. Soc. Amer. Proc. 30:661-662.

Swanson, N. P. 1965. Rotating boom rainfall simulator. Trans ASAE 8(1):71-72.

Turner, A. K., and K. A. Langlord. 1969. A rainfall simulator and associated facilities for hydrologic studies. J. Aust. Inst. Agr. Sciences. 35(2):115-199.

Walker, P. H., J. Hutka, A. J. Moss and P. I. A. Kinnell. 1977. Use of a versatile experimental system for soil erosion studies. Soil Sci. Amer. J. 41(3):610-612.

Wilm, H. G. 1943. The application and measurement of artificial rainfall on types FA and F infiltrometers. Trans. Amer. Geophys. Union 24:480-484.

PALOUSE RAINFALL SIMULATOR

G. D. Bubenzer, Myron Molnau, D. K. McCool[1]

Rainfall in the Palouse region of the Pacific Northwest is characterized by its long duration and low intensity. Much of the annual rainfall occurs during the late fall and winter months when the ground is often frozen and/or snow covered. While the erosive power of the rainfall is much lower than in other parts of the United States, the unique hydrologic, topographic, agronomic, and soil conditions combine to create severe water erosion problems. The Palouse rainfall simulator is being developed to closely simulate these low intensity storms and will be used for infiltration and erosion research.

Raindrop data collected by McCool were analyzed for drop size distribution and intensity levels. Most of the events sampled had intensities of less than 2.5 mm/hr. Rainfall from these low intensity storms produces little runoff or erosion unless it contributes to snow melt or occurs while the soil is thawing at the surface. Erosion under these conditions can be both widespread and severe. Severe erosion is also associated with the infrequent but more intense isolated summer thunderstorm. A design intensity range of 1 to 50 mm/hr was, therefore, selected to cover both storm conditions. The median drop size distribution from 13 storms with intensities greater than 2.5 mm/hr were used to determine the design drop size distribution. None of the observed storms exceeded 10 mm/hr in intensity. The median drop diameter was 1.7 mm with D_{10} of 0.8 mm and D_{90} of 2.6 mm (Figure 1). The 1/4 HH 14 W SQ Full Jet solid cone square nozzle produced by Spraying Systems, Inc. was selected because of the relatively uniform areal coverage at low flow volumes. The drop size distribution, as provided by the company, corresponded closely to the desired distribution (Figure 1). The uniformity coefficient ranged from 80 to 90 percent over a two meter square area at all intensities.

The 1/4 HH 14 W SQ Full Jet nozzle was designed to operate at an intensity near the upper end of the design range. In order to reduce the intensity, a rotating disk unit similar to that developed by Amerman et al. (1970) and modified by Rawitz et al. (1972) was used. Two modifications have been made in the units described above. First, because of the wide spray angle of the nozzle, spray caught on the lip of the return trough. The water formed large drops which fell upon the plot. The size of the opening was increased and the lip height around the opening decreased.

1/Associate Professor, Agricultural Engineering Department, University of Wisconsin - Madison, Agricultural Engineer, USDA-SEA-AR, Pullman, Washington, and Professor, Agricultural Engineering Department, University of Idaho - Moscow.

Second, the double thickness of the rotating disk was eliminated. Use of the single rotating disk with a single lip improved the uniformity of application at the lower intensity levels.

A single nozzle unit for use as an infiltrometer has been constructed. The nozzle and rotor unit are mounted on a telescoping frame which can be adjusted for varying slope conditions. The maximum plot size is two meters square. A 568 liter polyethylene tank is used as the water supply. A Hypro Series 7700 Roller pump is used to provide water to the infiltrometer.

A second unit, currently under construction, will be a totally self-contained trailer mounted unit containing two nozzle units and capable of raining on plots two meters wide by five meters long. Additional plot length may be obtained by combining the units. The nozzle units may be rotated to either side of the trailer so that tests may be conducted on two plots for each trailer setting.

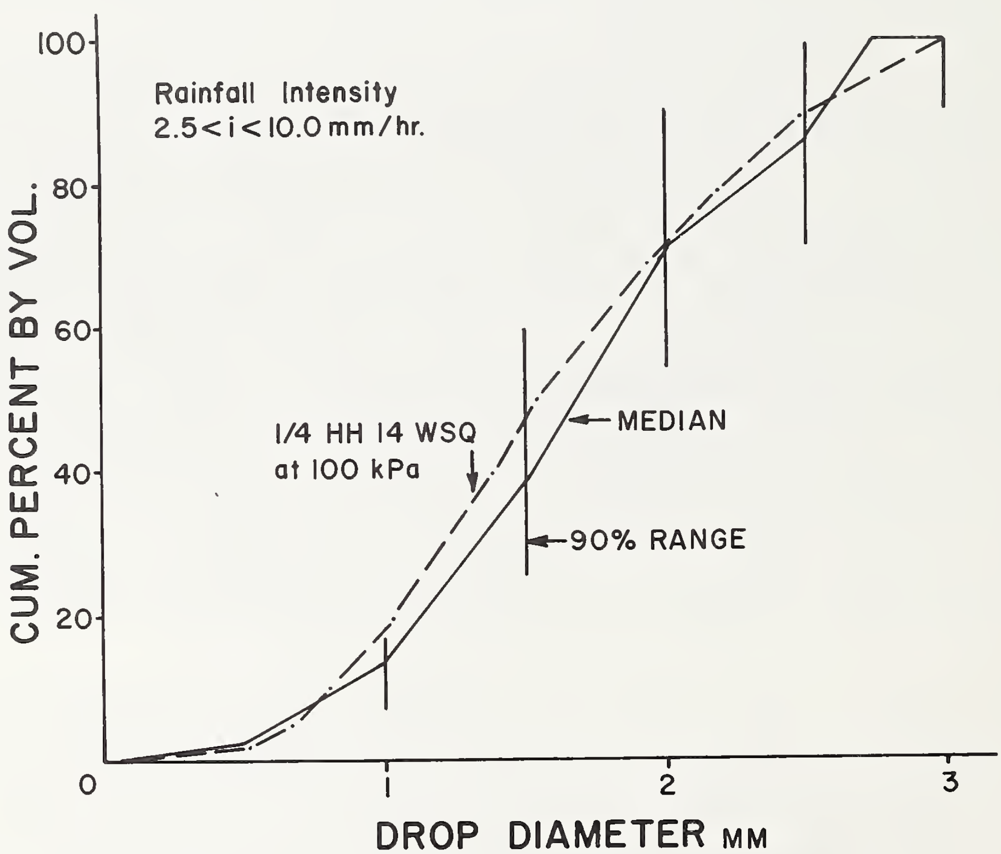


Figure 1. Typical drop size distribution for rainfall event in the Palouse region and distribution of the 1/4 HH 14 W SQ nozzle operating at 41.4 kPa. (*Unpublished data by McCool)

REFERENCES

Amerman, C. R., D. I. Hillel, and A. E. Peterson. 1970. A variable-intensity sprinkling intiltrometer. Soil Sci Soc Amer Proc 34:830-832.

Rawitz, E., M. Margolin, and D. Hillel. 1972. An improved variable-intensity sprinkling infiltrometer. Soil Sci Soc Amer Proc 36:533-535.

ACKNOWLEDGEMENTS

Research supported by the Agricultural Experiment Station, University of Idaho. Moscow, Idaho.

Manufacturer's names are included for the benefit of the readers and do not imply endorsement by the authors or sponsors of the research.

INFILTRATION CONTROL RESEARCH AS EXPEDITED BY RAINFALL AND RAINWATER SIMULATION TECHNIQUES

Robert M. Dixon, SEA Soil Scientist[1/]

This is a brief summary of an ongoing research program directed to developing principles and practices for controlling infiltration for the purpose of increasing and stabilizing crop production. Research utility of rainfall and rainwater simulation techniques is briefly discussed.

The research results reported herein represent minor extensions of the experimental works of Free et al. (1948), Duley and Kelly (1939), Kostiakov (1932), Gardner (1962), and Bertrand and Parr (1960), and minor additions to Darcy-based flow theory as developed and described by Klute (1973), Philip (1969), and Childs (1969).

Locations Studied

Infiltration research was initiated in Wisconsin in the early sixties and later conducted in Montana, Nevada, and Arizona. Plant-sized infiltration systems were studied, since the prime objective of the research was to gain control of infiltration to, in turn, improve the crop plant's microhydrologic and microclimatic environment.

Principles Developed

First, an attempt was made to understand the *natural infiltration system* of the crop plant through an extensive literature review. This involved compilation and organization of a large number of infiltration facts, many of which seemed to be contradictory. After collecting some infiltration data myself, these facts were synthesized into a general principle called the *two-flow system* concept of infiltration (Dixon, 1966). This concept postulates that infiltration involves the flow of air and water in two interacting flow systems (namely, the *channel* system and *capillary* system), and that soil surface conditions control the infiltration contribution of the channel system. After collecting some more data in Montana, the two-flow system concept was refined slightly and renamed the *channel system* concept (Dixon, 1971; Dixon and Peterson, 1971). This concept holds that the typical soil contains a large-pore system, and that microroughness and macroporosity of the soil surface regulate flow of air and water in this system during an infiltration event.

The channel system concept was further refined in Nevada, and then referred to as the *air-earth interface* (AEI) concept (Dixon, 1972). This concept

1/ Southwest Rangeland Watershed Research Center, USDA-SEA-AR, 442 E. 7th Street, Tucson AZ 85705.

states that the *microroughness and macroporosity of the air-earth interface control infiltration by regulating flow of water and displaced soil air in underlying macropore and micropore systems.* Thus, the *AEI* infiltration concept describes the influence of two physical conditions on the flow of two fluids in two subsystems of interconnected soil pores.

The preceding three concepts for controlling water infiltration differ primarily in their emphasis or in the frame of reference from which infiltration mechanisms are described. These concepts represent an evolution, progressing from a basic understanding of plant-sized infiltration systems to practical control of infiltration through soil surface management (Dixon, 1975a).

Development and refinement of infiltration control theory required use of rainfall and rainwater simulators to provide some of the conditions experienced by a natural system during the course of an infiltration event (Bertrand and Parr, 1960; Dixon and Peterson, 1964 and 1968). Sometimes these simulators were used in combination to isolate various components of the AEI infiltration system (Dixon, 1966).

In Wisconsin, the infiltration contribution of the macropore system was isolated by using sprinkling and flooding infiltrometers in side-by-side runs. This contribution was also isolated by sprinkling water onto soil surfaces with and without either organic or simulated mulches (window screen) to absorb water drop impact (Dixon, 1966).

In Nevada, the soil air pressure effect was isolated by using a *border-irrigation infiltrometer* in runs made before and during actual border irrigation (Dixon and Linden, 1972). This device is capable of measuring infiltration during overland or channel flows of irrigation waters and rainwaters which produce up to 30 cm of head.

The border-irrigation infiltrometer led to the development of the *effective surface head* (ESH) concept which states that ESH is the hydraulic manifestation (or hydraulic equivalent) of surface microroughness and macroporosity with ESH defined as the surface water pressure head minus the soil air pressure head (Dixon, 1974).

The ESH concept in turn led to the invention of the *closed-top infiltrometer* which is designed to produce a realistic range of effective surface heads surrounding zero or the ambient atmospheric pressure. This infiltrometer is useful in isolating the infiltration effect of soil air pressure and the infiltration contribution of the macropore system (Dixon, 1975b). Not only the rate, but also the route of infiltrating water was determined (as a function of ESH) by adding a readily adsorbed dye to the water within a modified closed-top infiltrometer (Linden and Dixon, 1976).

The principle of the closed-top infiltrometer is presently being utilized in the development of a sprinkling infiltrometer that can simulate realistic soil air pressures such as would be produced by intense summer rains on sloping land. A *natural rainfall* infiltrometer is also being developed which utilizes some of the components of the modified Purdue sprinkling infiltrometer. This new infiltrometer should help evaluate data from the rainfall, rainwater, and soil air pressure simulating devices which were discussed previously.

Kostiakov's equation (Kostiakov, 1932), $I_v = AT^B$, has been re-interpreted in light of the AEI concept (Dixon, 1976, 1977a, 1978b; Dixon, et al. 1978; Dixon and Simanton, 1979). Kostiakov's equation is shown to be a general infiltration formulation with the equations of Darcy (1856), Ostashev (1936), and Philip (1957) representing special cases. Parameters A and B are shown to be functions of the microroughness-macroporosity parameter or its hydraulic equivalent, effective surface head. Coefficient A may be viewed as an infiltration

capacity parameter, whereas exponent B is a parameter reflecting the rate of infiltration abatement.

To expedite fitting of 2-parameter infiltration equations to sprinkling infiltrometer data, an overland flow tube is used to introduce massive slugs of water for rapid runoff induction at the beginning of the infiltration run.

Practice Developed

Recently in Tucson, a new land treatment method and a new machine (called *land imprinting* and the *land imprinter*, respectively) have been developed for practical application of the AEI-ESH concept (Dixon, 1977b and 1978a; and Dixon and Simanton, 1977). This machine, through its mechanical action and the ensuing biotic activities, converts a microsmooth microporous AEI with a negative ESH to a microrough macroporous surface with a positive ESH.

Utility Suggested

Since the microrough and macroporous surface can infiltrate most of the rainwater from a 100-year storm (Dixon et al. 1978), imprinting can be effective in holding soil and water resources in place to increase and stabilize crop production to, in turn, meet present-day needs for food, feed, fodder, fiber, fuel, and fertilizer; while at the same time be effective in improving land resources for even greater productive capacity in the future.

Also, since microsmooth and microporous surfaces shed most of the rainwater from a 100-year storm (Dixon et al. 1978), thereby directly contributing to increased aridity of the crop plant's environment (and indirectly through erosional loss of soil resources), land imprinting has the potential for arresting and reversing world-wide desertification or man-induced degradation of land resources. Desertification is estimated to annually cost the world 16 billion dollars in lost agricultural production, and is expected to reduce the arable land area by one-third by the year 2000, at which time world food needs will have doubled (Biswas, 1978).

Research Planned

Future research directions will be steered by the progress cited above. Some general and specific research objectives to be pursued are:

(1) To evaluate ESH under natural rainfall on sloping and flat land areas.
(2) To relate plant litter to ESH and the microroughness-macroporosity parameter.
(3) To determine the microclimatic, microhydrologic, and biotic impacts of land imprinting.
(4) To improve imprint geometries for successful crop stand establishment under adverse edaphic and climatic conditions.
(5) To evaluate land imprint seeding as a method for arresting and reversing desertification.

Literature Cited

Biswas, M. R. 1978. United Nations Conference on Desertification in Retrospect, International Institute for Applied Systems Analysis. A-2361, Laxenburg, Austria. 36 p.

Bertrand, A. R., and Parr, J. F. 1960. Development of a portable sprinkling infiltrometer. Trans. 7th International Congress of Soil Science, 1:433-440. Madison, WI.

Childs, E. C. 1969. Surface infiltration. An introduction to the physical basis of soil water phenomena. John Wiley and Sons, Ltd., New York, p. 274-294.

Darcy, H. P. G. 1856. Les Fontaines Publiques de la Ville de Dijon. Dalmont, Paris.

Dixon, R. M. 1966. Water infiltration responses to soil management practices. PhD Thesis, Univ. Wisconsin, 175 p., Univ. Microfilms, Ann Arbor, MI (Order No. 66-5903, Diss. Abstr. XXVII:4).

Dixon, R. M. 1971. Infiltration role of large soil pores: A channel system concept. Proc. 3rd International Seminar for Hydrology Professors on Biological Effects in the Hydrological Cycle. IHD-NSF-UNESCO and Purdue Univ.

Dixon, R. M. 1972. Controlling infiltration in bimodal porous soils: Air-earth interface concept. Proc. 2nd Symp. Fundamentals of Transport in Porous Media. IAHR-ISSS and University of Guelph. 1:102-117.

Dixon, R. M. 1974. Effective surface heads and infiltration control. ASA Agronomy Abstracts, p. 165.

Dixon, R. M. 1975a. Infiltration control through soil surface management. Proc. Symp. on Watershed Management. Irrigation and Drainage Division, ASCE and Utah State University. p. 543-567.

Dixon, R. M. 1975b. Design and use of closed-top infiltrometers. Soil Sci. Soc. Amer. Proc. 39:755-763.

Dixon, R. M. 1976. Comments on "Derivation of an equation of infiltration," by H. J. Morel-Seytoux and J. Kanja. Water Resources Research, AGU 12(1): 116-118.

Dixon, R. M. 1977a. Air-earth interface concept for wide-range control of infiltration. Annual Meeting of Amer. Soc. of Agri. Engineers, Raleigh, NC. Paper No. 70-2062, 33 p.

Dixon, R. M. 1977b. New soil implement makes a good impression. Crops and Soil Magazine, 29:14-16.

Dixon, R. M. 1978a. Soil imprinting for increasing land productivity. Invitational Paper for Joint Air Resources and Soil Resources Symposium of Future Crop Production Capabilities. 33rd Annual Meeting, Soil Conservation Soc. Amer., Denver, CO, July 30 - August 3.

Dixon, R. M. 1978b. Water infiltration control in rangelands. Proc. 1st International Rangeland Congress, p. 322-325, Denver, CO, August 14-18.

Dixon, R. M. 1972. Soil air pressure and water infiltration under border irrigation. Soil Sci. Soc. Amer. Proc. 36:948-953.

Dixon, R. M., and Peterson, A. E. 1964. Construction and operation of a modified spray infiltrometer and a flood infiltrometer. Wisc. Agr. Exp. Sta. Res. Rpt. 15.

Dixon, R. M., and Peterson, A. E. 1968. A vacuum system for accumulating runoff from infiltrometers. Soil Sci. Soc. Amer. Proc. 32:123-125.

Dixon, R. M., and Peterson, A. E. 1971. Water infiltration control: A channel system concept. Soil Sci. Soc. Amer. Proc. 35:968-973.

Dixon, R. M., and Simanton, J. R. 1977. A land imprinter for revegtation of barren land areas through infiltration control. Proc. Amer. Water Resources Assn. and Arizona Acad. Sci., Las Vegas, NV. 7:79-88.

Dixon, R. M., and Simanton, J. R. 1979. Water infiltration processes and air-earth interface conditions. In: Surface and Subsurface Hydrology. p. 314-336, Water Resources Publications, Fort Collins, CO.

Dixon, R. M., Simanton, J. R., and Lane, L. J. 1978. Simple time-power functions for rainwater infiltration and runoff. Proc. 22nd Annual Meeting of the Arizona-Nevada Academy of Sci. Amer. Water Resources Assoc. 8:79-89.

Duley, F. L., and Kelly, L. L. 1939. Effect of soil type, slope, and surface conditions on intake of water. Nebraska Agricultural Experiment Station Bulletin 112, 31 p.

Free, G. R., Browning, G. M., and Musgrave, G. W. 1940. Relative infiltration and related principle characteristics of certain soils. USDA Tech. Bull. 112, 51 p.

Gardner, W. H. 1962. How water moves in the soil. Crops and Soils. 15:7-11.

Linden, D. R., and Dixon, R. M. 1976. Soil air pressure effects on route and rate of infiltration. Soil Sci. Soc. of Amer. Jour. 40:963-965.

Klute, 1973. Soil water flow theory and its application in field situations. In: Field Soil Water Regime. Soil Sci. Soc. Amer., Madison, WI.

Kostiakov, A. N. 1932. On the dynamics of the coefficient of water percolation in soils and the necessity of studying it from the dynamic point of view for the purpose of amelioration. Trans. 6th Comm. ISSS, Russian Pt. A., p. 17-21.

Ostashev, N. A. 1936. The law of distribution of moisture in soils and methods for the study of the same. International Conf. Soil Mechanics and Foundations Engineering Proc., Vol. 1 (Sect. K):227-229.

Philip, J. R. 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Sci. 84:257-264.

Philip, J. R. 1969. Theory of infiltration. Advan. Hydrosci. 5:215-296.

CURRENT RAINFALL SIMULATOR ACTIVITIES AT LAFAYETTE, INDIANA 1/

G. R. Foster 2/

USES OF RAINFALL SIMULATOR

The USDA-SEA erosion research unit at Lafayette, Indiana extensively uses rainfall simulators in erosion, overland flow and infiltration field and laboratory research. Some studies are very applied, like the study of the effect of tillage on erosion using a Meyer-McCune rainulator and 12 ft x 35 ft field plots. Some field studies are very basic like the rill erosion study where the influence of a nonerodible layer about 4 inches below the soil surface was investigated. Other field studies are between basic and applied. A rainulator is being used to isolate individual and interactive tillage factors including cover, roughness, and degree of disturbance on erosion. A rainulator and field plots are also being used to study deposition by overland flow on concave slopes and in strips of mulch and grass. A Purdue Sprinkling Infiltrometer is the major tool in a field study to identify the effect of conservation tillage on infiltration.

Rainfall simulators are used in laboratory studies on sediment transport and deposition by overland flow and soil crusting and particle detachment by raindrop impact. These simulators include both oscillating nozzles and capillary tube types. In addition, the Agricultural Engineering Department at Purdue has a 14 ft x 14 ft capillary tube simulator to study overland flow hydrology while a 4 ft x 14 ft capillary tube simulator is available in the Civil Engineering School to study overland flow turbulence in the presence of rainfall.

SIMULATORS AS A RESEARCH TOOL

The main objectives of the research program at Lafayette is: (1) to understand basic erosion mechanics, (2) to develop reliable erosion prediction techniques, and (3) to develop improved erosion control practices. Rainfall simulation like modeling, statistics, natural runoff plots, laboratory soils analysis, etc. is a tool that has its place in both basic and applied research. However, it must be properly used, and the data must be carefully interpreted.

ADVANTAGES OF RAINFALL SIMULATORS

Some things can be accomplished with rainfall simulators that cannot be with natural rainfall. Variability and complex interactions cause erosion data from natural runoff plots to be practically useless for analyzing basic erosion relationships with our current level of understanding. Data from carefully planned and executed rainfall simulator experiments can identify erosion

---

1/ Contribution from the Soil, Water, and Air Sciences, North Central Region, USDA-Science and Education Administration, in cooperation with the Purdue Agricultural Experiment Station. Purdue Journal No. 7626

2/ Hydraulic Engineer, USDA, and Assistant Professor, Agricultural Engineering; Purdue University, West Lafayette, Indiana.

processes that would otherwise be masked in natural plot data. The most obvious advantage of rainfall simulators is that data can be obtained without waiting for natural rainfall that either occurs infrequently or at inopportune times. Another major advantage is that rainfall simulator plots are easy to abandon. We remove our instrumentation and move to new areas each year unless the study objectives require reusing the plots. Our plots are always on cooperators' land sparing us the trouble of property maintenance. We tend to use plots better suited to the study rather than using on-hand plots. Although simulators are expensive to operate, they may give more information per dollar than do either natural runoff plots or watersheds designed to provide the same answers. However, rainfall simulator plots, natural runoff plots, and watersheds are all needed in a well balanced erosion research program.

RAINFALL SIMULATOR PROBLEMS

Rainfall simulator setup and tear down is time consuming and troublesome. Mechanical, electrical, and plumbing systems are often too complex, unreliable, and require considerable maintenance. Many rainfall simulators are limited to two or three spatially uniform intensities. Time between nozzle passes is excessive for some simulators using intermittent spray nozzle.

Plots normally used with ranfall simulators also have limitations. Most plots are too small to study contouring, and most are too narrow for natural rilling patterns to develop. Small pans and areas (5 square ft) are easy to use but are inadequate to study USLE soil erodibility, steepness, length and cover-management factors; tillage; or sediment transport.

Instrumentation used in field erosion research has lagged behind laboratory instrumentation. Instruments are needed to measure flow velocity, depth, and rate without attentuation, time lag, or calibration errors caused by deposition. Laboratory and field instrumentation is needed to quickly and easily determine particle characteristics (size, density, and shape) of the sediment as it is eroded and transported. Also, instrumentation is needed to rapidly and easily characterize surface roughness, cover, and flow pattern with a minimum of external data processing.

Limitations of equipment and necessary experimental design limit the extent that data can be extrapolated to natural conditions. Ways of using a small number of uniform intensity storms to characterize annual rainfall erosivity as it varys with locale are needed. Also, ways of using data from short plots to represent long plots are needed.

Yet, with these limitations rainfall simulation continues to a major reseach tool. The limitations emphasize that rainfall simulators be carefully used.

USE OF THE ROCKY MOUNTAIN INFILTROMETER AND A MODULAR-TYPE INFILTROMETER ON RANGELANDS IN UTAH

Gerald F. Gifford, Utah State University

The Rocky Mountain Infiltrometer

The Rocky Mountain infiltrometer has been adequately described by Dortignac (1951). We currently use the infiltrometer in much the same form as originally described, though we run three plots at a time in contrast to one as described by Dortignac (Figure 1). From time to time we have modified the original plot size (0.23 m^2) by increasing either the length of plot or the width. If plot size is increased much beyond the original 0.23 m^2, then only two plots may be run at one time. Individual plots are installed by driving the sharpened edges into the soil surface to a depth of about 7.5 cm with a specially constructed hammer. The nozzles used are Type F nozzles with raindrop characteristics as given by Meyer and McCune (1958). The infiltrometer stimulates a storm somewhat characteristic of a high intensity convectional type thunderstorm. Rainfall application rates are usually in the range of 7.5 to 10 cm/hr, and each set of three plots requires about 210 liters of water for a 30-minute run. Use of trough gages on either side of each plot allows careful monitoring of rainfall application rates on each plot. An adjustable canvas wind shield is used to minimize wind disturbance and raindrop drift. Where comparisons are to be made among season or years, then plots are pre-wet prior to application of simulated rainfall to eliminate confounding effects of antecedent moisture.

The kinetic energy of a simulated storm with the Rocky Mountain infiltrometer can be related to that of a similar natural rainstorm by considering drop diameter and velocity upon impact (Meyer 1965). Drop diameter, however, is directly proportional to the mass of a raindrop and the mass of the accumulated raindrops (rainfall amount) can be assumed to be the same for both simulated and natural rainfall. This leaves only the ratio of the velocities squared as a parameter for comparing simulated to natural rainfall. Mathematically, the above discussion is:

$$\frac{M_s V_s^2}{M_n V_n^2} = \frac{\text{K.E. of simulated rainfall}}{\text{K. E. of natural rainfall}} = \text{Relative K.E. of simulated storm}$$

where: M_s = mass of the simulated rainfall
V_s = velocity of the simulated rainfall
M_n = mass of the natural rainfall
V_n = velocity of the natural rainfall

But, $M_s = M_n$, and assuming a mean drop diameter from a Type-F nozzle as being approximately 3.7 mm and an average fall height of 2.2 m with an impact

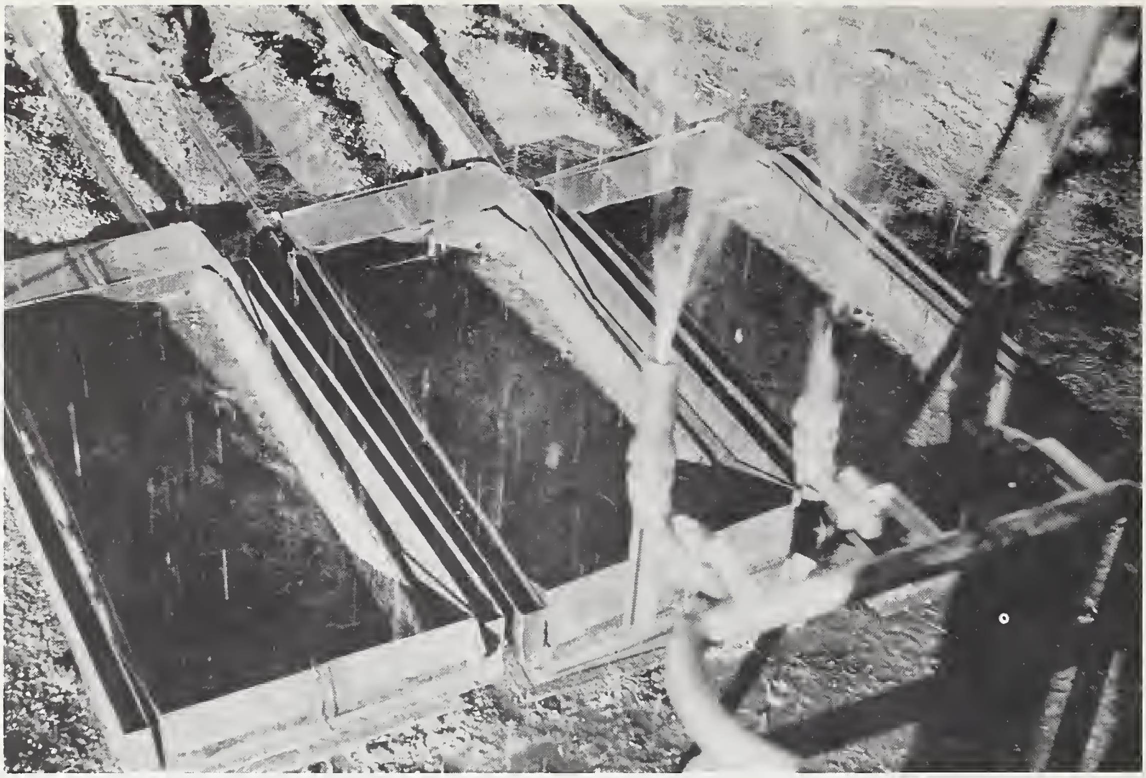


Figure 1. General view of Rocky Mountain rainfall simulator and associated plots.

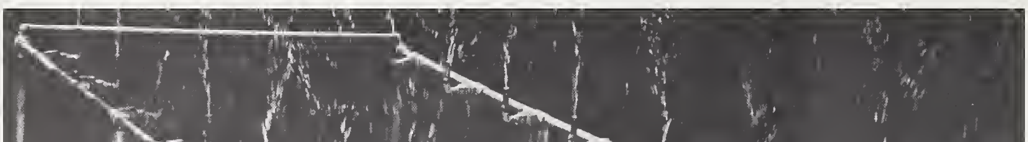


Figure 2. Infiltrometer with 14 Type-F nozzles.

velocity of 5.95 m sec^{-1}, and knowing that natural raindrops with a mean drop size diameter of 3.7 mm would have a terminal velocity of about 9.06 m sec^{-1}, then

$$\frac{V_s^2}{V_n^2} = \frac{(5.95)^2}{(9.06)^2} = 0.43$$

The Type-F nozzles have also been adapted to simulators somewhat larger than the Rocky Mountain infiltrometer (Figure 2). These larger rainfall simulators have been used in studying range improvement practices in Nevada, for studying salt transport on rangelands in Utah, and for studying hydrology of treated oil shale in eastern Utah and western Colorado.

Experience gained in obtaining infiltrometer data from approximately 2,500 Rocky Mountain infiltrometer plots over a wide variety of conditions in Utah and elsewhere has indicated some definite limitations in use of the instrument, limitations which have also been noted by Gaither and Buckhouse (1979): steepness of slope, accessibility of sampling sites, rocky or stony soils, low overstory vegetation (with resultant interception of simulated rainfall), and presence of slash or dense litter layers.

A Modular-Type Infiltrometer

We have been using a modular-type rainfall simulator originally designed by Meeuwig (1971) and later modified according to Malekuti and Gifford (1978) for hydrologic studies primarily on mining spoils and tailings deposits. The simulator is shown in Figure 3 and may be described as follows:

The infiltrometer will deliver simulated rainfall at intensities ranging from about 3 to 25 cm hr^{-1} over a plot size of 3,413 cm^2. Raindrop size is approximately 2.5 mm, and relative to a natural storm the drops deliver about 28% of the expected kinetic energy. The water chamber is rotated in a horizontal position to insure equal water pressure on the needles and somewhat random drop position over the plot.

1. Water chamber: 60.9 cm by 60.9 cm by 2.5 cm plexiglass box.
2. Flow meter: regulates flow from the reservoir to the chamber and therefore the rate of rainfall.
3. Reservoir: 25 liter polyethylene container connected to the flow meter by flexible plastic tubing.
4. Electric motor: powered by a six volt battery to rotate the chamber (used to distribute raindrop positions).
5. Hypodermic needles: 517 stainless steel tubes with a 0.476 mm inner tube diameter and a 0.635 mm outer diameter. The tubes project 3.2 mm above and 9.5 mm below the plexiglass base of the chamber.

There are no plot frames, only a trough on the downslope edge of the plot for delivering plot runoff to a bucket (Figure 4). Because the entire plot is sprinkled, infiltration rates are exaggerated somewhat due to lateral water movement. The simulator, however, is portable, it is well suited to steep slopes and to rocky soils, and it requires only about 25 liters of water per 30 minutes at 7.5 cm hr^{-1}.

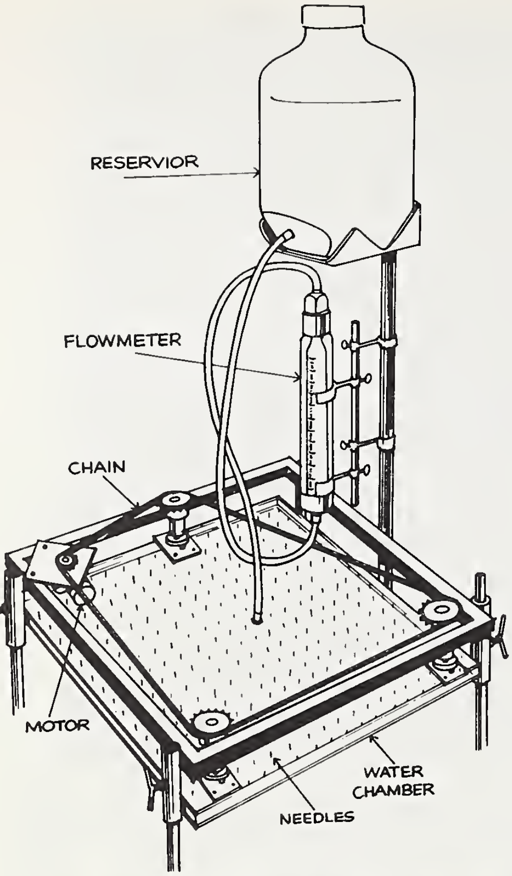


Figure 3. Sketch of the modular-type infiltrometer.

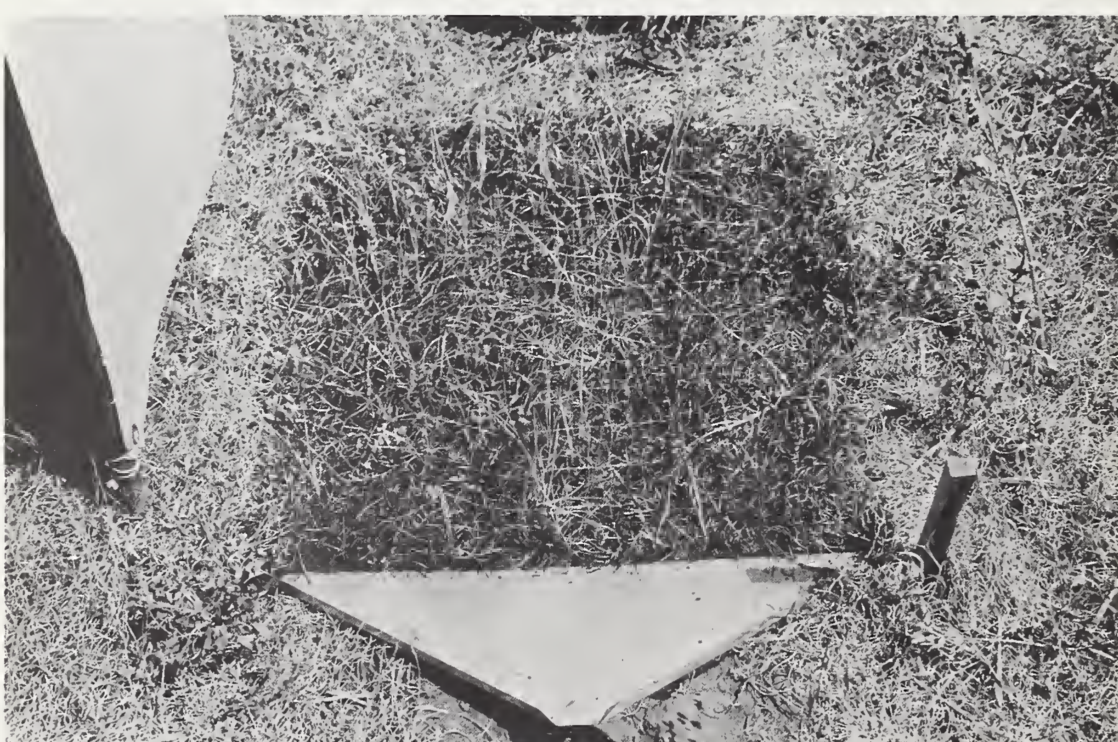


Figure 4. Wetted plot with trough at bottom edge.

Literature Cited

Dortignac, E. J. 1951. Design and operation of Rocky Mountain infiltrometer. U.S. Forest Serv., Rocky Mt. Forest & Range Exp. Sta. Paper No. 5: 68 p.

Gaither, R. E., and J. C. Buckhouse. 1979. Some comparisons of Rocky Mountain infiltrometer capacities across several vegetation zones. Abstr. of Paper Presented, 32nd Annual Meeting, Soc. for Range Manage., Feb. 12-15.

Malekuti, A., and G. F. Gifford. 1978. Natural vegetation as a source of diffuse salt within the colorado River Basin. Water Resour. Bull. 14:195-205.

Meeuwig, R. O. 1971. Infiltration and water repellency in granitic soils. U.S. Forest Serv. Res. Paper INT-111: 20 p.

Meyer, L. D. 1965. Simulation of rainfall for soil erosion research. Trans. A.S.A.E. 8:63-65.

Meyer, L. D., and D. L. McCune. 1958. Rainfall simulator for runoff plots. Agr. Eng. 39:644-648.

EVALUATION OF THE EFFECTS OF INTENSIVE LIVESTOCK GRAZING SYSTEMS THROUGH RAINFALL SIMULATION

P. D. Green, BLM hydrologist[1/]

INTRODUCTION

In discussing the Rainfall Simulation study currently underway within the Bureau of Land Management (BLM), it is necessary to briefly review the origin of the project.

The BLM has initiated site specific Environmental Statements (ESs) on livestock grazing in response to a court order of December 30, 1974. As of September 1978, eight of 145 ESs have been completed through the draft stage. The last ESs are due for completion in 1988. The acres involved range from less than 50,000 to over 11,000,000 per ES. The end product will be 145 ESs for livestock grazing on public lands.

In early 1976, after BLM started preparing the site specific ESs, it became apparent there was a lack of adequate data to evaluate the effects of intensive livestock grazing systems on water resources. Specific tools were lacking to evaluate potential changes in the grazing season, grazing intensity or cyclic grazing on the following parameters: sediment yield, infiltration, runoff, or water quality (chemical and bacterial).

In view of the data deficiencies, a study was proposed in 1976 entitled, "Determination of Runoff and Sediment Yield by Rainfall Simulation Methods."

RAINFALL SIMULATOR

In March 1978, our rainfall simulator was completed. The simulator is a sprinkler type, portable unit covering a 65 ft. by 45 ft. plot at 2"/hr. (Lusby, 1977). Rainfall is measured in 25 storage gages. Runoff is diverted into a Parshall flume through coated trenches along the bottom of the plot. Stage is recorded with a Stevens Type F recorder. Water samples are collected with a pumping sampler (ISCO). Plot boundaries are identified by metal borders and coated trenches.

OBJECTIVES

Most of the ESs have used the SCS Curve Number (CN) technique to predict the impacts on runoff. Curve numbers were determined through a model

---

1/ Bureau of Land Management, Denver Service Center, Division of Special Studies, Denver, Colorado 80225.

developed at Utah State (Gifford and Hawkins, 1976) where steady state infiltration is a function of the hydrologic soil group and grazing intensity and the curve number is a function of infiltration, cover density and the vegetation type. The project objectives were established to validate the Utah State model and to evaluate the impacts of grazing on sediment yield.

Objective 1 - Determine if grazing intensity, forage utilization or ecological range condition can be used to predict a CN for a soil-vegetative complex given a season of use.

Objective 2 - Determine if grazing intensity, utilization or ecological range condition can be used to predict infiltration rates for a soil-vegetative complex given a season of use.

Objective 3 - Determine if the hydrologic soil group can be used to predict infiltration rates on a relic (good to excellent range condition) soil-vegetation complex.

Objective 4 - Determine if physical characteristic of a basin can be used to predict grazing intensity given a pasture stocking rate, class of stock and season of use.

Objective 5 - Determine if grazing intensity, utilization or ecological range condition can be used to predict sediment yield on a rainfall simulation plot.

Objective 6 - Determine the relationship of infiltration or curve numbers between small simulator plots (400 ft^2) and large simulator plots (2600 ft^2).

Objective 7 - Determine the infiltration recovery rate of a soil-vegetative complex when livestock are removed.

Objective 8 - Determine the infiltration impact rate due to livestock grazing.

SIMULATION AREAS

To date, we have operated in the McCain Valley in Southern California, San Luis Valley in Southern Colorado, Green Mountain area in Western Wyoming and in the Alamo Reservoir area in Arizona. We plan on extending these areas this year to Elko, Nevada, and Lewistown, Montana, with the addition of a second simulator.

SUMMARY

Correlations developed with a rainfall simulator are relative values until they can be related to actual rainfall events. What is needed is a tool that uses rainfall simulator plot values as input parameters to a hydrologic model. We are cooperating with the USGS (Denver) on a process oriented hydrologic modeling effort, with this objective in mind.

LITERATURE CITED

Gifford, Gerald F. and Hawkins, Richard H.
1976. Hydrologic Impacts of Grazing on Infiltration: A Critical Review. Water Resources Research 14(2) April 1978.

Lusby, Gregg C.
1977. Determination of Runoff and Sediment Yield by Rainfall Simulation. Erosion: Research Techniques, Erodibility and Sediment Delivery: 1977, Edited by Terrence J. Toy, Geo Abstracts LTD., Norwich, England.

RAINFALL SIMULATION AND WATERSHED RESEARCH

Clifton W. Johnson, SEA *hydraulic engineer*[1/]

The days of watersheds without rainfall simulators and rainfall simulators without watersheds appear to be nearly past. We recognize the great contribution watershed research has made in providing hydrologic and sedimentation data for design of water utilization and control structures; but see the need for rainfall simulation to study on-site infiltration and erosion as influenced by widely varying rainfall, soil, cover, and other factors.

Infiltration and erosion studies by rainfall simulator methods are needed to compliment historical and ongoing watershed research at the Northwest Watershed Research Center, Boise, Idaho, to fully understand the on-site processes and factors which influence long-measured runoff and sediment yield. Now we can utilize the precipitation, climatic, soil, cover, runoff, and sediment data in choosing the proper rainfall simulator system appropriate for our rangeland conditions. The challenge is to choose from among the many rainfall simulators a suitable device or devices for use on steep slopes, rocky soils, and sagebrush vegetation and to generate runoff and erosion similar to that recorded from watersheds.

Examples of records from the Reynolds Creek Experimental Watershed, which can be used in choosing a suitable rainfall simulator, are as follows:

1. The average 15-minute rainfall intensity was 30 mm/ha from the 32 highest-intensity events in a 16-year record at a single raingage. The maximum recorded rainfall intensity was 18 mm in 4 minutes.

2. The average yearly peak streamflow was about 22 m^3/sec in a 16-year record and ranged from about 2 to 108 m^3/sec. All, except two of 16 yearly peaks, were caused by winter and spring storms associated with snowmelt, rain-on-snow, or frozen soil.

3. Measured rill erosion from an intense thunderstorm on sparsely vegetated rangelands was about 116 tonnes/ha on a 40 percent slope.

4. Average slope gradient on much of the watershed is about 25 percent and some areas with visible erosion exceed a slope of 60 percent.

5. Rock cover with particles exceeding about 6 mm diameter is 30 to 40 percent on about 15 percent of the watershed area.

1/ Northwest Watershed Research Center, Science and Education Administration, U. S. Department of Agriculture, Boise, Idaho 83705.

6. Vegetative ground cover ranges from about 45 percent with 250 mm/yr precipitation to about 85 percent with 1140 mm/yr precipitation. Sagebrush canopy cover ranges from about 10 to 40 percent.

When rainfall simulation and watershed research are fully integrated, our understanding of the total system will be much improved; both approaches have much to offer in solving the complex problems before us.

RAINFALL SIMULATION ON SURFACE MINE ROADS

Robert S. Johnston and Eric Sundberg, research hydrologists[1/]

Surface runoff and sediment yield from surface mine roads is being studied under simulated rainfall conditions. Data generated in this cooperative study by the USDA Forest Service, Intermountain Forest and Range Experiment Station and Montana State University will be used to develop and test a predictive model for runoff and sediment yield of mine roads. This model is based on the ROad SEDiment (ROSED) model developed by Simons and Li at Colorado State University.

The rainfall simulator used in this study is a modified C.S.U. model. A detailed description of the simulator and calibration results are described in other papers in this proceedings by Lusby and Neff. Ten road sections on two phosphate mines in southeastern Idaho and three coal mines in eastern Montana were studied during the summer of 1978. Road sections were selected to test a wide variety of road design and soil characteristics. The basic simulator design of five rows of five sprinklers was modified to provide the largest plot size possible for each road section while maintaining the design spacing between adjacent sprinklers. Plot sizes varied from 16 x 130 feet to 30 x 30 feet. Surface mine roads are usually constructed with earth berms along the road edges. Either these berms or the center crown of the road was used for the side boundaries of the plots. Water was diverted away from the plot at the top of the section and runoff was diverted to one side of the road at the bottom of the plot.

Discharge, measured with a Replogle flume and FW-1 recorder, and sediment samples were collected from both dry and wet runs on each test section. Dry runs were ended after runoff had peaked and the hydrograph trace appeared to be constant, usually 10 to 15 minutes. Wet runs were usually longer to observe any changes in runoff or sediment yields with time. All runs were terminated when wind speeds exceeded 5 mph to insure uniform distribution of water on the plot.

[1/] Intermountain Forest and Range Experiment Station, USDA Forest Service, Forestry Sciences Laboratory, 860 North 12th East, Logan, UT 84321; and Department of Civil Engineering and Engineering Mechanics, Montana State University, Bozeman, MT 59717, respectively.

Discharge increased very rapidly in response to the low infiltration, low surface storage capacity, low roughness characteristics, and rapid concentration of runoff from the road surface. Frequently, several intermediate peaks were noted on the rising hydrograph in response to the lag time in the contribution of runoff from different areas of the plot. Once peaked, discharge usually remained fairly constant until the end of rainfall, when recession flow decreased rapidly. Sediment concentrations followed a similar pattern as discharge, rising very rapidly, holding constant and decreasing very rapidly at the end of the run. The constant level of sediment concentrations during the longer runs indicate the availability of sediment was not a limiting factor in sediment yields, at least for runoff of 30 to 40 minute durations.

Advantages of the type of rainfall simulator we used are ease of movement, and flexibility of plot size. Among the disadvantages are the inability to easily vary rainfall intensities. One problem we experienced was deposition of sediment in the throat of the flume during recession flows, which required constant removal.

Data collected during this study are being summarized and analyzed. Model development is progressing and initial results should be completed by October this year.

EXPERIMENTAL INVESTIGATION OF SOIL DETACHMENT BY RAINDROP IMPACTS

M. Martinez, Graduate Student, L. J. Lane, SEA Hydrologist, and
M. M. Fogel, Professor of Watershed Management[1/]

INTRODUCTION

Soil detachment due to raindrop impact is an important part of the soil erosion process in upland areas. Consequently, the mechanisms of raindrop impact in dislodging and transporting of soil particles should be studied independently and analyzed in combination in order to understand water erosion (1).

A rainfall simulator (rotadisk rainulator) developed at the University of Arizona and Purdue University was used to study detachment of soil particles by raindrop impact. The rotadisk simulator produces artificial rainfall with median drop size, drop velocity, and kinetic energy comparable to natural rainfall (2). This study involved the following objectives:

(1) To determine soil detachment and transport by raindrop impact using a rainfall simulator.

(2) To relate detachment rates to vegetative cover, soil land slope, and rainfall intensity.

(3) To determine the influence of erosion pavement on soil detachment rates.

Experimental Procedure

Six study sites were selected considering soil particle size in the land surface and slope steepness. A site was located at the University of Arizona Water Resources Laboratory which has almost flat silt loam soils. Three sites were located at Atterbury Experimental Watershed, where the soils are sandy loam with gravel in the surface, and the amount of gravel increases with slope steepness. Montijo Flat and Lucky Hills sites were located at Walnut Gulch Experimental Watershed, where the soils are sandy loam with 2 percent slope, and erosion pavement (gravelly soil) with 11 percent slope, respectively.

Since the rotadisk rainulator covers uniformly a 1.3 x 1.3 m plot, an

1/ University of Arizona, Southwest Rangeland Watershed Research Center, 442 E. Seventh Street, Tucson, AZ 85705, and University of Arizona, respectively.

apparatus was constructed and attached to the frame of the simulator to limit the applied rainfall to a 10 x 70 cm source area. The remainder of the plot was left as a target area for the detached soil particles. The target area was covered with 10 x 170 cm or 10 x 75 cm paper strips in horizontal and vertical configuration related to the source area to record the amount of soil deposited on each strip. The procedure was to make three 5-min applications of rainfall in 44, 86, and 118 mm/hr bursts in each site, and then to collect the paper strips with deposited soil. These paper strips were oven-dried to obtain the amount of soil deposited on each strip. At Lucky Hills, a plot with extensive erosion pavement, the gravel was removed, and the same 5-min application of rainfall were made.

Results and Discussion

The amount of soil detachment at different distances from the source area of each site are shown in Table 1. The amount and rate of soil detached

Table 1.--Measurements of soil detached at different sites using horizontal paper strips.

Site	Intensity	Distance From Source Area (cm)							
	mm/hr	10	20	30	40	50	60	70	Total
Lucky Hills	44	0.63	0.22	0.16	0.04	0.00	0.00	0.00	1.05
	86	0.695	0.355	0.185	0.080	0.085	0.050	0.075	1.53
	118	0.815	0.350	0.160	0.110	0.095	0.060	0.080	1.67
Lucky Hills (disturbed)	44	1.665	0.695	0.335	0.185	0.155	0.105	0.080	3.22
	86	1.555	0.740	0.445	0.260	0.155	0.120	0.135	3.41
	118	2.740	1.415	0.785	0.485	0.260	0.170	0.145	6.00
Montijo	44	0.620	0.265	0.130	0.120	0.070	0.045	0.055	1.305
	86	1.850	0.665	0.365	0.155	0.110	0.065	0.075	3.285
	118	3.900	1.475	0.555	0.325	0.185	0.130	0.090	6.660
Prince Road	44	2.265	1.00	0.59	0.34	0.27	0.11	0.18	4.755
	68	2.725	1.445	0.66	0.41	0.22	0.16	0.08	5.700
	86	4.835	2.225	1.235	0.72	0.385	0.24	0.18	9.820
	118	5.19	2.31	1.29	0.83	0.595	0.44	0.375	11.030
Atterbury 1	44	1.805	0.54	0.195	0.105	0.065	0.010	0.000	2.72
	68	3.815	1.055	0.335	0.235	0.090	0.070	0.095	5.695
	86	4.82	1.52	0.655	0.375	0.338	0.315	0.378	14.096
	118	4.99	2.045	0.865	0.385	0.185	0.130	0.220	8.820
Atterbury 3	44	1.13	0.405	0.165	0.130	0.080	0.035	0.045	1.990
	68	2.135	1.090	0.590	0.380	0.265	0.160	0.145	4.765
	86	3.065	1.030	0.735	0.605	0.260	0.175	0.220	6.090
	118	3.735	1.555	0.630	0.415	0.295	0.125	0.030	6.785
Atterbury 5	44	0.865	0.445	0.205	0.175	0.095	0.09	0.080	1.955
	68	0.900	0.380	0.265	0.140	0.105	0.080	0.065	1.935
	86	1.10	0.735	0.390	0.245	0.175	0.125	0.090	2.860
	118	2.025	1.085	0.395	0.315	0.160	0.125	0.075	4.180

increased with increasing rainfall intensity. However, for the Lucky Hills plot with extensive erosion pavement, the influence of rainfall intensity was slight. When the surface pavement was removed, the influence of intensity was magnified (Lucky Hills disturbed site). The maximum amount and rate of soil detached was found for silt loam soils at Prince Road Site, and it was observed that soil detachment decreased with increasing amount and increasing median particle size of the erosion pavements. These results show an agreement with those reported by Farmer (3) where he pointed out that maximum detachability of soil particles is between diameters of .3 to .1 mm, and that when the size of soil particle increases, there is a reduction in detachability due to increasing particle mass.

It was found that an exponential decay function explains the variation of amount of soil with distance from the source area. The same decay function was obtained from the data presented by Palmer and Van Haveren (4). This indicates that when a raindrop strikes soil surface, the material splashed is distributed exponentially around the impacting point.

SUMMARY

A simple procedure was developed to measure soil detachment and transport by raindrop impact, and we have determined relationship between plot characteristics, rainfall intensities, and soil detachment/transport rate. Rainfall simulators appear to be a useful tool in investigations of erosion by raindrop impact.

LITERATURE CITED

(1) Ellison, W. D.
1947. Soil erosion studies. Part 1. Agricultural Engineering, p. 145-146.

(2) Morin, J. D., D. Goldberg, and I. Seginer.
1967. A rainfall simulator with a rotating disk. Trans. ASAE 10:(1)44-49.

(3) Farmer, E. E.
1973. Relative detachability of soil particles by simulated rainfall. Soil Sci. Soc. Amer. Proc. 37, p. 629-632.

(4) Palmer, E. E., and B. P. Van Haveren.
1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA Forest Service Research Paper INT-100. 14 pp.

CURRENT RAINFALL SIMULATORS AND RESEARCH ACTIVITIES

L. D. Meyer[1/]

Most current research uses a small multiple-intensity rainfall simulator to evaluate interrill erosion, runoff, and sediment sizes from crop-row sideslopes for various soils and cropping conditions. A similar rainfall simulator is used in a laboratory study of the sediment transport capability of row-furrow runoff for different flow rates, furrow gradients, and sediment sizes. Plans have been developed for a larger multiple-intensity rainfall simulator to evaluate rill erosion or erosion along crop rows for lengths up to 40 meters, but a prototype has not been completed.

The small rainfall simulator can apply dozens of rainfall intensities from less than 10 mm/hr to more than 100 mm/hr on interrill areas of about 1 meter square or less. It can be set up and taken down in less than an hour and is usually hauled in a pickup. The user has an option of choosing a 80150 Veejet nozzle which gives a drop size distribution, drop fall velocities, and kinetic energy very close to natural rainfall above 25 mm/hr or a 80100 Veejet with characteristics of rain at about 10 mm/hr. The nozzle oscillates back and forth across the plot with a delay after each pass. The length of the delay, selected at multiples of 0.1 second on an electronic timer that activates a clutch-brake, determines the intensity of application. Nozzle height is usually 3 meters and pressure is 41 N/m^2. Water that is not sprayed on the plot and border area is caught and returned to the supply tank.

Since erosion is often serious from land that is intensively farmed to row-crops and since much of the sediment originates from row sideslopes, most plots are a short section of crop row. Runoff from the row sideslopes is collected in a trough at the row furrow and sampled at intervals of about 5 minutes. These samples are analyzed to determine erosion rate, runoff rate, and sediment size distribution. Some studies of chemical losses have been conducted and more are planned. To date, erosion, runoff, and sediment sizes have been evaluated for 10 soils, at rainfall intensities of 10, 25, 67, and 105 mm/hr. One soil was studied during different crop stages of cotton: after the first cultivation, at half-canopy, at full canopy, and after harvest to evaluate any change in row-sideslope erosion during the crop season. Companion plots with all cover removed were studied at the same time to evaluate the change in soil

1/ Agricultural Engineer, USDA Sedimentation Laboratory, Science and Education Administration, U. S. Department of Agriculture, Oxford, MS 38655.

erodibility through the season, independent of the cover effects. Additional soils and cropping conditions will be studied in the future.

Related laboratory research is being conducted to determine how much of the sediment delivered to the furrows from the row sideslopes will be transported along the furrows. A channel cross section common to cotton-land furrows is used to study the effects of furrow slope, flow rate, and sediment size in the presence and absence of rainfall on the sediment transport rate. Sand-sized sediment has been studied, and future studies are planned to study the transport rate of smaller and less dense particles such as are common in sediment from aggregated agricultural soils.

The basic design has been developed for a multiple-intensity rainfall simulator to study erosion from rills or rows up to 40 meters long. Many of the principles used in the small multiple-intensity rainfall simulator are incorporated, with emphasis on rapid set up and take down characteristics. One section has been built, but a prototype has not been completed.

REFERENCES

(1) Meyer, L. D. and W. C. Harmon
1977. "Multiple-Intensity Rainfall Simulator for Erosion Research on Row Sideslopes". Scheduled for publication in Trans. ASAE and distributed as ASAE Paper 77-2025.

(2) Meyer, L. D., W. C. Harmon, and L. L. McDowell.
1978. "Sediment Sizes Eroded from Row Sideslopes." Distributed as ASAE Paper No. 78-2518.

CURRENT RAINFALL SIMULATION ACTIVITIES
OF THE SEDIMENT YIELD UNIT

C. K. Mutchler
research leader[1/]

We are employing the rainulator and a simulator borrowed from Dr. Meyer in our erosion research to complement erosion plot research. Their operation and use has been well documented by Don Meyer and doesn't require any elaboration here.

Projects that used the rainulator, which is a field plot rainfall simulator, are:

1. 1976-1977--Effect of hipping on soil erosion (Mutchler). Bedding with a disk-hipper is commonly used by cotton farmers in Mississippi. Heavy land is often left bedded from fall to planting - lighter soils are left bedded for shorter periods of time. We evaluated the practice using side-by-side paired hipped, and flat plots and two 75-ft. units of the rainulator. Storms were applied as a dry run followed by a wet run, both 2.5 inches for an hour. The primary analysis was a calculation of the ratio of soil loss from the treatments

$$C= \frac{\text{SL hipped}}{\text{SL flat}} = 2.5$$

which shows the erosion hazard from leaving land hipped for long periods of time.

2. 1977--Effect of slope length on soil loss from low slopes (Mutchler). Bedded plots were established using lengths of 75, 150, 300, and 600 feet, all on 0.2 percent slope. The rainulator was used on the bottom 75-ft. and part circle sprinklers on the upper part of the plots. Comparison of soil loss from rainulator and irrigated plots yielded a factor of rain loss = 1.6 times irrigation loss. This factor was used to adjust data from the longer plots to a rainulator basis. Other adjustments were made in the data to correct for slope irregularities and for differing application rates. Adjusted soil losses indicated a slope-length exponent of m = 0.15 for the wet runs and m = 0.03 for the dry runs. These results aided the decision by Wischmeier to lower the exponent to m = 0.2 for slopes less than 1 percent (Ag Handbook 537).

3. 1978--Effect of percent slope on erosion (Murphree). Very little data is available for slope effects on soil loss from slopes under about 3

1/ Sedimentation Laboratory, Science and Education Administration, U.S. Department of Agriculture, Oxford, MS 38655.

percent. Two 75-foot plots were run simultaneously with the rainulator for comparing soil loss from 0.1 and 0.2, 0.5 and 1.0, and 2.0 and 3.0 percent slopes. At the time of raining on the first plots, all the other plots in the replication were covered to keep the antecedent moisture constant for the dry run. Results from this experiment have not been fully analyzed.

A small rainfall simulator (borrowed from Don Meyer) was used by McGregor in 1978 to study the effect of cotton canopy on rainfall energy that causes erosion. Single plots were run with measurements being made of drop sizes falling in flour targets set at ground level. Data from this experiment have not been fully analyzed.

4. 1979--We plan to continue rainulator work on soil loss from low slopes and to make K-factor measurements from a major soil type that occurs on low slopes. Note that a considerable analytical effort will be required to adjust K-factor plot data for storm types and antecedent moistures that occur during a "typical" year.

SIMULATOR ACTIVITIES--Sidney, Montana

Earl L. Neff, SEA, research hydraulic engineer

At Sidney we built a portable rainfall simulator of the same design as those used by Greg Lusby of the USGS and Pat Green of the BLM which were developed from the work at Colorado State University's rainfall facility. The design consists of five rows of five sprinklers each spaced 20 feet apart. The maximum plot size that can be efficiently used is about 4,000 square feet. The sprinkler heads are Rain Jet Model 78C placed on risers about 11 feet above the ground surface. Water is provided to supply lines for each sprinkler row by pumping from butyl rubber storage bags. Sprinkler head pressure is controlled by pressure regulators in each sprinkler riser.

We tested this simulator to determine:

1. Uniformity of aerial distribution.

2. Effects of wind.

3. Drop size distribution.

4. Kinetic energy produced.

We found that: (1) Uniformity of aerial distribution suffers as plot size increases because of the edge effects near the outside rows of sprinklers. However, uniformity is very good for plots up to about 3,000 square feet (50' x 60') and is satisfactory for plots up to 4,200 square feet (60' x 70'), (2) Aerial distribution suffers when average wind velocities exceed 6-7 mph. Below this threshold, wind effects are minor, (3) Drops produced by the simulator are smaller than those produced by natural thunderstorms with the same rainfall intensity (see the table of comparisons), (4) The kinetic energy produced by the simulator at an intensity of 2 inches/hour is about 40% of that produced by natural rainfall at the same intensity (see the table of comparisons).

Calculations also indicate that 50% of the total kinetic energy is produced by drops d_{70} or larger and 75% is produced by drops d_{50} or larger in both simulator and natural rainfall at intensities of 2 inches/hour.

This simulator is a flexible design that permits it to accommodate plots of various sizes and shapes by either adding more rows of sprinklers or lengthening the existing rows. Plot size is limited only by pump capacity, water supply, and length of time in a run.

USDA, Science & Education Administration, AR, Northern Plains Soil and Water Research Center, Sidney, Montana 59270.

Comparison between Simulator and Natural Rainfall Characteristics
2 inch/hour Intensity

Characteristic	Simulator	Natural
Drop Size - mm		
Max	3.0	5.5
d_{90}	2.2	3.8
d_{70}	1.6	2.9
d_{50}	1.2	2.4
d_{30}	0.9	1.9
d_{10}	0.4	1.2
Drop Velocity - % of Terminal		
Max drop size	83	100
d_{90} drop size	88	100
d_{70} drop size	93	100
d_{50} drop size	98	100
d_{30} drop size	100	100
d_{10} drop size	100	100
Kinetic Energy-ft-tons/acre-inch	400	1000

A RAINFALL SIMULATOR FOR SMALL LABORATORY SAMPLES

M. J. M. Römkens[1/]

Laboratory simulator was designed to study rain infiltration, surface sealing effects under steady state and transient conditions, and rainfall detachment on small cores (3.5 inches O.D.) in the laboratory. The principle of this rainfall simulator is to appply rainfall on a continuous basis to small laboratory samples with a uniform raindrop distribution at a known but constant intensity and a known energy of impact. This rainulator consists of a closely packed assembly of syringes in which the rate of plunger movement is related to the intensity. Rotational and lateral motions of the syringe assembly insures a unifrom drop impact distribution. Tests show the observed intensity to be within +2.5% of the predicted values while the coefficient of variation of drop impact is between 6-7%.

REFERENCES CITED

(1) Römkens, M. J. M.., L. F. Glenn, D. W. Nelson, and C. B. Roth, 1974. Proc. Soil Sci. Soc. Amer. 39:158-160.

1/ Soil Scientist (Soil Physics), USDA Sedimentation Laboratory, Oxford, MS 38655.

CURRENT RAINFALL SIMULATORS AND SIMULATOR ACTIVITIES AT FORT COLLINS, COLORADO

Roger E. Smith, Hydraulic Engineer
USDA-SEA-AR, FT. Collins, CO

Both drip-type and sprinkling-type rainfall simulation are being employed at Fort Collins by SEA-AR in hydrologic research. The CSU outdoor Rainfall-Runoff Experimental Facility (RREF) has been in operation for some 11 years (Holland, 1969) and a sprinkling-type grid system that was developed and applied on this 1.25-acre facility was recently adapted by the USGS for portable plot use. In the Colorado State University hydraulics laboratory, drip-type modules of various sizes have been employed since 1969 in various research experiments.

The CSU RREF Simulator

The history of the search for a suitable rainfall simulator for the 1.25-acre butyl-covered watershed at CSU is outlined by Holland (1969). After attempts to use large oscillating gun-type irrigation nozzles, the feasibility of a grid application with small sprinkler heads was studied by C. Brent Cluff (now at WRRC, University of Arizona) and R. E. Smith under the direction of D. A. Woolhiser. Several types of sprinkler heads, including common commercial lawn sprinklers and lawn sprinkler system heads were tested. Tests concentrated on spatial pattern of intensity and distribution of drop sizes. Given the intended use, primary consideration was to find a spray pattern that could be used as an element in a grid of nozzles that would produce an optimum uniformity, without requiring excessive numbers of nozzles and yet allow a range of intensities. Also considered, though secondarily, was the realism of the drop sizes produced.

A computer simulation was used to investigate how an experimentally measured spatial distribution pattern would perform as an element of a large pattern.

Although all available nozzles were not tested, the study did conclude that a very acceptable pattern could be obtained with the Rainjet 78C on a basic triangular grid comprised of 40 ft equilateral spacings. The final design incorporated enough nozzles to superimpose up to eight basic grids in overlays to allow intensities of approximately 0.5 to 4 in. per hour (1.5 to 10 cm per hour). Table 1 shows how the sampled coefficient of variation of intensity varies as additional nozzles are added within the system. The details of each nozzle riser are shown in Figure 1. Figure 2 shows how the simulator's drop size distribution compares to samples of natural rainfall obtained by Laws and Parsons (1943).

Laboratory Drip-type Simulators

Laboratory experiments first employed drip-type simulators at CSU by ARS in 1969 (Smith and Woolhiser, 1970) in an experimental one-dimensional infil-

trating watershed surface study. Drip modules were designed following the University of Illinois system (Chow and Harbaugh, 1965) but were only 2 in. (5 cm) wide. Drippers were only a few inches above the surface since rainfall energy was not important.

Presently a 4 ft (1.22 m) wide by 40 ft (12.2 m) long flume equipped with Chow-type drip producing units at 10 ft elevation is being employed in studies of runoff and erosion processes. Drops of some 3.63 mm diameter achieve about 77 percent of terminal velocity (Peterson, 1977). Future plans for this facility include variation of drop size and full height in studies of interrill erosion.

LITERATURE CITED

(1) Chow, Ven Te, and T. E. Harbaugh.
1965. Raindrop Production for Laboratory Watershed Experimentation. J. of Geophys. Res., 70(24):6111-6119, Dec.

(2) Holland, M. E.
1969. Colorado State University Experimental Rainfall-Runoff Facility-Design and Testing of Rainfall Systems.

(3) Laws, J. O., and D. A. Parsons.
1943. The Relation of Raindrop-Size to Intensity. Trans. A.G.U. 24:452-460.

(4) Peterson, Roger J.
1977. Laboratory Simulation of Soil Erosion. M.S. Thesis, Colorado State University, Fort Collins.

(5) Smith, R. E., and D. A. Woolhiser.
1971. Mathematical Simulation of Infiltrating Watersheds. Hydrology Paper No. 47, Colorado State University, Fort Collins.

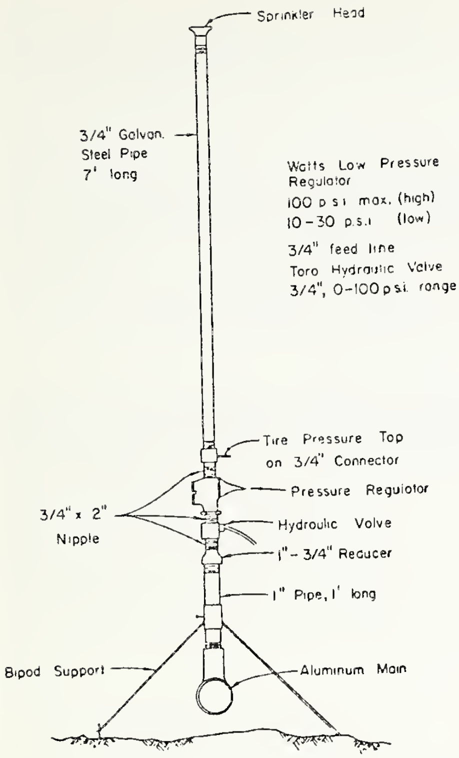


Figure 1. Sprinkler Riser Assembly.

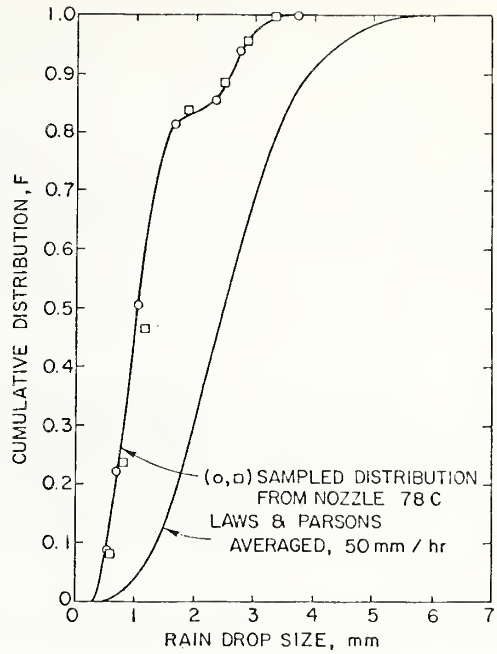


Figure 2. Drop size distributions produced by the sprinkler head.

Table 1
PARAMETERS OF RAINFALL DISTRIBUTION
OF PROTOTYPE GRID SYSTEM

Average (in./hr.)	Coefficient of Variation
0.64	0.199
1.19	0.089
1.22	0.131
1.26	0.073
2.76	0.049
4.93	0.037

FIELD PLOT RAINFALL SIMULATION (ROTATING-BOOM RAINFALL SIMULATOR) LINCOLN, NEBRASKA

Norris P. Swanson, SEA Agricultural Engineer and Research Leader[1/]

The objectives of field plot rainfall simulation at Lincoln have been primarily measurements of runoff and erosion for comparison of tillage practices, mulch treatments, and washoff of fertilizers. Simulation is of the higher intensity storms which cause the erosion and runoff problems in the western Corn Belt and eastern Great Plains. Expected significant differences are usually found between practices, and total infiltration is significant. However, possible significant differences in final intake rates on fine textured, slowly permeable soils are often obscured by the small but unavoidable errors in measurement of application and runoff with intensities of 2.5 and 5.0 in/h.

A "sprinkler simulator" was designed at Lincoln in 1957 and subsequently used on long, 400 to 1000 ft, furrow-irrigated plots with row-crop canopies (Swanson, 1960). A rainulator (Meyer and McCune, 1958) was constructed at Lincoln in 1960. Dedrick compared the sprinkler simulator and the rainulator (1963). After wind flattened the rainulator on a field site in 1962, a "better way" to meet our needs was sought and the rotating-boom simulator was envisioned. The rotating-boom simulator eliminated electrical circuitry and solenoid valves, greatly reduced the number of moving parts, and provided a readily movable unit on a trailer mounting. However, simultaneous storms are provided on only two plot areas of 14 by 35 ft. Seventy foot plot lengths require two simulators.

Application characteristics of the Spraying Systems Company, Veejet 80100 nozzle, detailed in Special Report No. 81 (Meyer, 1958), and used on the rainulator made possible the conception and design of the rotating-boom simulator. The nozzles, spraying continuously, move in a circular path which is instantaneously perpendicular to the long dimension of the nozzle spray pattern. Ten booms, each 25 ft long, support 30 nozzles. Each nozzle is mounted on a manually operated globe valve. The nozzles are located on 5 ft spacings from the stem supporting the booms. Intensities of 2 1/2 and 5 in/h are obtained by operating 15 or 30 nozzles, requiring water supplies of 60 and 120 gpm. The nozzles spray downward from 9 ft above ground. Each discharges 4 gpm at 6 psi producing drop-size distributions similar to those of natural rainfall with near-terminal velocities after 8 ft of free fall. The booms are operated in a level plane to maintain uniform water pressure at all nozzles. A longer

---

1/ Agricultural Engineering Research Unit, Science and Education Administration, U.S. Department of Agriculture, Agricultural Engineering Building, University of Nebraska, Lincoln, Nebraska 68583.

(taller) stem has been used on more sloping plots to provide adequate nozzle height upslope.

Water is supplied to the booms through the stem to which the booms are attached. Close control of rainfall intensity is obtained by control of the water supply pressure. The trailer support tower, and stem bearings were adapted from a Vermeer Pow-R-Sprinkler. An air-cooled engine turns the stem at 3.5 to 4.0 rpm through a clutch, reversing transmission, a right-angle worm-drive reduction gear, safety clutch, chain and sprockets. The stem serves as an axle for the drive sprocket.

A rotating-boom simulator was constructed at Cornell (Agricultural Engineering Department) by R. D. Black with some improvisions. A hydraulic boom drive was used and the stem support tower was hinged by a hydraulic cylinder. Each nozzle had a Dole pressure regulator and the booms were operated in a plane parallel to the plot surface. More recently at Ames, John Laflen installed a hydraulic drive and placed a tandem axle under the trailer to greatly improve towing on the highway.

The auxiliary equipment and operational techniques employed are essentially the same as for the rainulator. Innovations conceived at Lincoln follow.

Control of intensity -- Nozzle pressure is most important to the intensity and depth of water applied in a simulated storm. Manual control through valves by an observer requires concentration and precision pressure gauges. Expensive pressure regulators were unsatisfactory over a period of time. The kinetic energy of the water initially entering the simulator results in a pressure surge with the start of nozzle discharge. This short-term, higher pressure does not introduce significant error, but it can damage and change the calibration of low range pressure gauges located on the booms.

An inexpensive pressure indicator-regulator device helps to control pressure surges and protects pressure gauges. An increase of 0.2 psi pressure on a 3-inch-diameter piston increases the force on the piston by 1.5 lbs. Two cylinders, 3-inch copper pipe, are mounted vertically on the water supply line on the simulator, each fitted with a piston and leather from a water pump cylinder. Each piston rod is connected with a clevis and pin to the middle of a lever arm. One end of each lever arm pivots on a stationary pin and the other end is fitted with an adjustable sliding weight. Holes are drilled in the upper cylinder walls to permit increasing amounts of water to escape as water pressure continues to raise the pistons. One of the cylinders has larger holes to bleed off water at higher pressure. The other cylinder has smaller holes and is weighted to operate at lower line pressures. The pistons and cylinders function both as accurate pressure gauges and safety valves. Water loss during normal operation is minimal. Nozzle pressures can be closely set and regulated and much of the initial pressure surge in starting up is bled off. "Quick drain" of the simulator is desirable to end the storm. Usually the supply hose at the simulator is disconnected immediately after the supply pump is stopped, permitting immediate drainage of the booms which slope slightly toward the stem. Timed readings of an in-line water meter assure that the desired intensity is being applied. The volume of water applied, as recorded by a water meter, is probably more accurate than the use of channels across the plots to

measure the depths of application during a storm.

Runoff measurement -- Providing gravity flow from collection troughs into flumes for runoff measurement requires time consuming and often damaging excavation on research plots. The use of compressed air or electrically powered sump pumps to deliver the runoff to a flume and sampler provides more advantages than additional problems. A 12- or 14-quart bucket with a concrete bottom shape to avoid sediment collection is utilized as a sump for the pump. The flumes are supported and leveled above ground level. Where plots are on very steep slopes, such as highway cuts and fills, runoff can be delivered through downspouts from collection troughs to flumes.

The larger and perhaps clumsier to transport and handle Leupold and Stevens water stage recorders provide rectilinear hydrographs that are easier to analyze than those from the FW-1 type recorders. The Leupold and Stevens recorders are easy to use with the flumes away from the undersimulated rainfall.

A mobile volumetric measuring device, "barrel trailer", was constructed at Lincoln, for accurate runoff measurement with high sediment loads. Two sets of three vertical cylinders were mounted on a trailer. Each cylinder consisted of two 55-gallon drums welded together, end to end, with conical bottoms attached, each bottom fitted with a large gate valve. Each cylinder was filled in turn. The gate valves provided rapid discharge and permitted probing from the bottom if rapid settling restricted the discharge.

Sampling runoff -- In most situations continuous fractional sampling of runoff over selected periods of time is highly desirable. Adding a slightly larger slot to the sampler designed by Meyer allows more uniform rates of sampling. Both slots are used with initial and low runoffs. As runoff increases the smaller slot is capped, and with near maximum runoff the small slot is uncapped and the larger slot capped. If analyses require large samples, both slots can be used. Used auto windshield wiper motors are an excellent source of reduction gear motors for battery powered samplers.

Samples for water stable aggregate analyses may need to be taken ahead of the intake if pumps are used. The effect of pump impellers on soil aggregates in runoff has not been documented and may vary with soils.

Plot preparation -- Earth blades are available for concrete saws and expedite the installation of plot edging and cutting through residues with minimum disturbance.

A vertical base plate across the lower end of the runoff plot and below the collection trough is needed to obstruct subsurface flow. The theory of subsurface flow can be well demonstrated on runoff plots. These plates should extend below the depth of tillage, 8- or 9-inch depths are desirable.

Application of asphalt emulsion on the soil along the inside of the plot edging and at the approach edge of the collection trough eliminates soil losses from those disturbed areas as well as washouts and leaks.

Successful rainfall simulation studies on contour planed and tilled plots can be conducted. Stabilization of the soil at the plot edging with asphalt emulsion is important. When appreciable volumes of water are impounded before "breakover" on a sloping plot the dimensions of the plot obviously limit the resulting erosion. However, data pertinent to initial intake and impoundment can be obtained. Continuation of the "storm" through "failure" on plots with contour mulch tillage has yielded significant differences with many treatments. The use of field plot simulators should not be restricted to treatments with up and down slope operations.

Simulation of added plot length -- Runoff generally increases directly with slope length, but soil loss increases approximately as the 3/2 power of length. Increased surface flow increases velocity, tractive force, and sediment transport ability of runoff. Simulation of increased slope length to provide conditions similar to those on the lower reaches of a long plot is possible. Water is uniformly introduced across the upper edge of a plot by jets. Energy from the jets is dissipated against a curved metal shield from which the water runs onto the plot. At Lincoln, added surface flows produced significant differences among treatments in the protection provided against water erosion where no significant differences were measured under simulated rainfall alone.

Overland flow velocity -- Overland flow velocity can be readily timed with salt injection (ammonium sulphate in solution) using electrodes in the plot discharge connected in series with a dry cell battery and a milliammeter.

Aggregate analyses -- Aggregate analyses made immediately in the field and later in the laboratory were compared by Dedrick and Swanson. We found that laboratory aggregate analyses can be made of the sediments in runoff without incurring significant error.

Plot preparation, operational techniques, and equipment are equal factors in the successful use of a rainfall simulator in research. Poor performance by any of the three will nullify usefulness of the data.

LITERATURE CITED

(1) Swanson, Norris P.
1960. Hydraulic characteristics of surface runoff from simulated rainfall on irrigation furrows. ARS 41-43, Soil and Water Conservation Research Division, Agricultural Research Service, USDA.

(2) Meyer, L.D., and McCune, D. L.
1958. Rainfall simulator for runoff plots. Agr. Engr. 39:644-648.

(3) Dedrick, A. R.
1963. A comparison of two sprinkler devices suitable for studying soil and water movement on field plots. M.S. Thesis, University of Nebraska, Lincoln.

(4) Meyer, L.D.
1958. An investigation of methods for simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles. Special Report No. 81, Soil and Water Conservation Research Division, Agricultural Research Service, USDA.

ROTATING BOOM RAINFALL SIMULATOR USE IN IOWA

By John M. Laflen

We have used the rotating boom rainfall simulator developed by Swanson for erosion and chemical loss studies in Iowa since 1974. We have studied the effect of conservation tillage on runoff and soil and chemical losses. We have also evaluated the effect of chemical placement on chemical losses, and studied plant nutrient losses from foliar fertilized soybeans.

Swanson's simulator has been modified to improve its transportability and reliability. We have mounted the simulator on a tandem trailer, and replaced the mechanical drive train for turning the boom with a hydraulic system. For leveling, we use hydraulic cylinders. The water distribution system has been left intact.

Typical tests, in recent years, have consisted of a single test of such duration that runoff rates reach equillibrium, usually about 1 1/2 hours. We have used a single intensity, 2.5 in/hr. We have added flow at the upper end to simulate slope length. We can operate the simulator up to 6 tests a day (12 plots) since time required to move the simulator is less than 1/2 hour. In 1978, we operated the simulator 3 times on 24 plots, 1 time on 12 plots, and 2 times on 48 plots. Additionally, a cooperator used the simulator 3 times on 32 plots. The total number of plot rains was 276. These were accomplished between May 26 and Aug. 20.

We have used a gravimetric method for flow rate measurement. We install a portable shelter below the plot for a technician to make measurements and collect samples directly from the collector. Thus, we avoid the use of flumes and pumps, since drainage from the area is by gravity. We do not collect samples or measure flow rates continuously, but we do collect samples for sediment concentrations over an interval of at least 1 minute. Other measurements we make include photographic measurements of crop canopy and crop residue (% of surface covered), residue weights, slopes, antecedent moisture, and flow velocity.

During field work, our crew usually consists of two people taking samples and measuring flow rates, a technician operating the simulator, one to three people installing collectors, helping move, measuring runoff velocities, collecting residue, and adding flow for length simulation. One or two scientists make measurements and supervise. Considerable time is required during non-field periods for sample processing and data reduction.

RAINFALL SIMULATOR ACTIVITIES AT THE NORTH CENTRAL SOIL CONSERVATION RESEARCH LABORATORY, MORRIS, MINNESOTA

By Robert A. Young

A section of rainulator was used on a 5 ft (1.5 m) by 15 ft (4.6 m) laboratory plot to measure soil characteristics of rill and interrill eroded soil from simulated rainfall on three different soils. These soils had widely varying initial soil characteristics and differed in their susceptibility to rill erosion. Results compared the particle-size distribution and the relative quantities of rill versus interrill eroded soil as well as differences in particle-size distribution with time, amount of erosion, and matrix soil characteristics.

Three agricultural soils from the Pacific Northwest (Pendleton, Oregon; Pullman, Washington; Boise, Idaho) were also subjected to simulated rainfall on the same laboratory plot. Erosion from rill and interrill areas was measured separately and sediment characteristics determined.

A rainulator was used to apply known amounts of rainfall energy on eight plots, 13.3 ft (4.1 m) by 35 ft (10.7 m), on which a history of wheel traffic had been established. Standard runoff collection procedures were modified to separate erosion and runoff in the wheel track from that occurring in the nontracked area. Various field and laboratory measurements were made on both soil and sediment samples to determine basic cause and effect relationships between wheel traffic, soil compaction, and erosion. Some of these included the density and stability of soil clods, surface roughness and porosity, clod size distribution, and aggregate and primary particle size distribution.

A standard rainulator, which is normally capable of running on plots up to 75 ft (22.9 m) long, was modified to be able to run on plots up to 150 ft (45.7 m) long. This modified rainulator, combined with a sprinkler system, was used to measure soil loss and runoff from 75 ft (22.9 m), 150 ft (45.7 m), 300 ft (91.4 m), and 450 ft (137.2 m) long plots. Results from these tests are being used to modify the slope length exponent of the Universal Soil Loss Equation for long slope lengths. At the same time, the feasibility of simulating runoff flow and soil erosion on long field slopes by introducing surface flow at the upper end of 75 ft (22.9 m) companion plots was tested.

A typical livestock feedlot was designed and instrumented to evaluate the ability of various land and cropping treatments to absorb and retain pollutants in rainfall runoff from livestock feedlots in general. A modified rainulator was used to induce runoff and erosion from 135 ft (41.2 m) long plots lying one-third within the feedlot itself and two-thirds outside the feedlot. For four different cropping treatments below the feedlot--corn, oats, orchard grass on rough plowing, and a mixture of sorghum-Sudan grass--runoff and

total solids removal were reduced by an average of 70 and 92 percent, respectively, as the discharge from the feedlot passed through the buffer strips. Concentrations of TN and TP were reduced by an average of 64 and 59 percent, respectively. NH_4-N and PO_4-P concentrations were similarly reduced but NO_3-N concentration in the runoff increased, mostly on the orchard grass and the oat buffer strips. All treatments resulted in significant reductions in the number of coliform organisms in the runoff water after passing through the vegetated buffer strips. Buffer strip lengths of 118 ft (35.8 m) would appear to be sufficient to reduce concentrations of both nutrients and microorganisms in feedlot runoff from summer rainstorms on feedlot areas of the size tested to an acceptable level.

APPENDIX I

Participants

Dr. W. H. Blackburn,
Range Science Department
Texas A&M University
College Station, Texas 77843

Dr. James E. Box, Soil Scientist
USDA-SEA-AR
Southern Piedmont Conservervation Research Center
P. O. Box 555
Watkinsville, Georgia 30677

Mr. John C. Brown, Watershed Management
Division of Renewable Natural Resources
University of Nevada
1000 Valley Road
Reno, Nevada 89512

Dr. Gary D. Bubenzer
Dept. of Agricultural Engineering
University of Wisconsin
460 Henry Mall
Madison, Wisconsin 53706

Dr. Robert M. Dixon, Soil Scientist
USDA-SEA-AR
Southwest Rangeland Watershed Research Center
442 East Seventh Street
Tucson, Arizona 85705

Dr. Robert E. Dohrenwend
Ford Forestry Center
Michigan Technological University
L'Anse, Michigan 49946

Dr. David A. Farrell, Hydraulic Engineer
NPS, USDA-SEA-AR
BARC-West, Building 005
Beltsville, Maryland 20705

Dr. George R. Foster, Hydraulic Engineer
USDA-SEA-AR
Agricultural Engineering Dept.
Purdue University
Lafayette, Indiana 47907

Dr. G. F. Gifford
College of Natural Resources
Watershed Science Unit
Utah State University
Logan, Utah 84822

Mr. P. D. Green
Bureau of Land Management
Building 50, Denver Federal Center
Denver, Colorado 80225

Mr. W. R. Hamon, Location Leader
USDA-SEA-AR
North Appalachian Experiment Watershed
P. O. Box 478
Coshocton, Ohio 43812

Dr. Richard H. Hawkins
Dept. of Natural Resources
Utah State University
Logan, Utah 84322

Dr. Clifton W. Johnson
USDA-SEA-AR
Northwest Watershed Research Center
Patti Plaza - 1175 South Orchard - Suite 116
Boise, Idaho 83705

Mr. Robert S. Johnston
Intermountain Forest and Range Experiment Station
Forestry Sciences Laboratory
860 North 12th Street
Logan, Utah 84321

Dr. John M. Laflen, Agricultural Engineer
USDA-SEA-AR
Iowa State University
111 Agricultural Engineering Building
Ames, Iowa 50011

Dr. Leonard J. Lane, Hydrologist
USDA-SEA-AR
Southwest Rangeland Watershed Research Center
442 East Seventh Street
Tucson, Arizona 85705

Dr. Robert Lichty
Geological Survey
P. O. Box 25046
Denver Federal Center - Stop 420
Denver, Colorado 80225

Mr. Gregg C. Lusby
Geological Survey
P. O. Box 25046
Denver Federal Center - Stop 420
Denver Colorado 80225

Mr. Mario Martinez
USDA-SEA-AR
Southwest Rangeland Watershed Research Center
442 East Seventh Street
Tucson, Arizona 85705

Dr. Don K. McCool, Agricultural Engineer
USDA-SEA-AR
Washington State University
253 Agricultural Engineering Building
Pullman, Washington 99164

Dr. L. Donald Meyer, Agricultural Engineer
USDA Sedimentation Laboratory
P. O. Box 1157
Oxford, Mississippi 38655

Dr. John E. Morrison, Jr., Agricultural Engineer
USDA-SEA-AR
Grassland-Soil & Water Research Laboratory
P. O. Box 748
Temple, Texas 76501

Dr. C. K. Mutchler, Agricultural Engineer
USDA Sedimentation Laboratory
P. O. Box 1157
Oxford, Mississippi 38655

Mr. Earl L. Neff, Research Hydraulic Engineer
USDA-SEA-AR
Northern Plains Soil & Water Research Center
P. O. Box 1109
Sidney, Montana 59270

Dr. James B. Pate, Assistant Area Director
USDA-SEA-AR
Arizona-New Mexico Area
2000 East Allen Road
Tucson, Arizona 85719

Dr. Kenneth G. Renard, Director
USDA-SEA-AR
Southwest Rangeland Watershed Research Center
442 East Seventh Street
Tucson, Arizona 85705

Mr. A. R. Robinson, Hydraulic Engineer
NPS, USDA-SEA-AR
BARC-West, Building 005
Beltsville, Maryland 20705

Dr. M. J. M. Romkens, Soil Scientist
USDA Sedimentation Laboratory
P. O. Box 1157
Oxford, Mississippi 38655

Dr. Roger E. Smith, Hydraulic Engineer
USDA-SEA-AR
Colorado State University
Engineering Research Center - Foothills Campus
Fort Collins, Colorado 80523

Mr. Eric Sundburg
Department of Civil Engineering
Montana State University
Bozeman, Montana 59715

Mr. Norris P. Swanson, Agricultural Engineer
USDA-SEA-AR
University of Nebraska
Agricultural Engineering Building
Lincoln, Nebraska 68583

Dr. Robert A. Young, Agricultural Engineer
USDA-SEA-AR
North Central Soil Conservation Research Center
Morris, Minnesota 56267

APPENDIX II

BIBLIOGRAPHY
RAINFALL SIMULATOR DESIGN AND OPERATION

Adams, J. E. 1965. A rainfall simulator and erodibility of some Iowa soils. Unpublished Ph. D. Thesis. Iowa State College.

Adams, John E., Don Kirkham, and Donald R. Nielsen. 1957. A portable infiltrometer and physical measurements of soil in place. Soil Sci. Soc. Am. Proc. 21(5):473.

Alfaro, J. F., and A. Y. Hachum. 1977. A simulation of smooth-variable intensity rainfall patterns. Water Resources Bull. 13(2):349.

Amerman, C. R., D. I. Hillel, and A. E. Peterson. 1970. A variable intensity sprinkling infiltrometer. Soil Sci. Soc. Am. Proc. 34(5):830.

Anderson, J. U., A. E. Stewart, and P. C. Gregory. 1968. A portable rainfall simulator and runoff sampler. New Mexico State University Agric. Exp. Stn. Res. Rep. 143. 5 p.

Barnes, O. K., and G. Costel. 1957. A mobile infiltrometer. Agron. J. 49:105.

Barnett, A. P., and A. E. Dooley. 1972. Erosion potential of nature and simulated rainfall compared. Trans. Am. Soc. Agric. Engr. 15(6):1112.

Basu, J. K., and N. B. Puranik. 1954. Erodibility studies by rainfall simulator--Section 4: Engineering Part 1. J. Soil and Water Conserv. in India 2:177.

Beale, W. E., T. C. Peele, and F. F. Lesesne. 1966. Infiltration rates of South Carolina soils during simulated rainfall. Tech. Bull. 1022.

Befani, A. N., N. F. Befani, Ed Goptchenko, A. G. Ivanenko, T. V. Odrova, and E. V. Terentyev. 1969. Experimental study of rainfall runoff. Int. Assoc. of Sci. Hydrol. Pub. No. 84:274.

Bertrand, Anson R., and James F. Parr. 1960. Development of a portable sprinkling infiltrometer. Int. Soc. Soil Sci., 7th Cong. Trans. 1:433.

Bertrand, Anson R., and James F. Parr. 1961. Design and operation of the Purdue sprinkling infiltrometer. Purdue University Agr. Exp. Stn. Res. Bull. No. 723. 16 p.

Beutner, E. L., R. R. Gaebe, and R. E. Horton. 1940. Sprinkled plot runoff and infiltration experiments on Arizona desert soils. Trans. Am. Geophys. Union 21:550. 30 p.

Bisal, F. 1950. Calibration of splash cup for soil erosion studies. Agric. Engr. 31:621.

Black, P. E. 1970. Runoff from watershed models. Water Resources Res. 6(2):465.

Black, P. E. 1972. Hydrograph responses to geomorphic model watershed characteristics and precipitation variables. J. Hydrol. 17(4):309.

Blackburn, W. H. 1973. Infiltration rate and sediment production of selected plant communities and soils in five rangelands in Nevada. University of Nevada. 99 p.

Blackburn, W. H., R. O. Meeuwig, and C. M. Skau. 1974. A mobile infiltrometer for use on rangeland. J. Range Manage. 27(4):322.

Blaisdell, F. W. 1938. Report on development of artificial rainfall apparatus Type D-1. USDA Mimeographed Report.

Borst, H. L. 1940. Rain simulator studies of the effect of slope on erosion and runoff. USDA-SCS. TP No. 36. 32 p.

Borst, H. L. 1942. The effect of mulching and methods of cultivation in runoff and erosion from Muskingum silt loam. Agric. Engr. 23:19.

Borst, H. L., and R. Woodburn. 1939. Contour cultivation studies with the rainfall simulator. Soil Conserv. 5:12.

Bovey, R. W., and J. D. Diaz-Colon. 1969. Effect of simulated rainfall on herbicide performance. Weed Sci. 17(2):154.

Brakensiek, D. L., W. L. Rawls, and W. R. Hamon. 1979. Application of an infiltrometer system for describing infiltration into soils. Trans. Am. Soc. Agric. Engr. (In press).

Brazil, L. E. 1976. A water quality model of overland flow. Unpublished M.S. Thesis, Colorado State University. 141 p.

Brockman, F. E., W. B. Duke, and J. F. Hunt. 1975. A rainfall simulator for pesticide leaching studies. Weed Sci. 23(6):533

Bubenzer, G. D. 1970. Effect of drop size and impact velocity on the detachment of soils under simulated rainfall. Unpublished Ph. D. Thesis, University of Illinois, Urbana. 120 p.

Bubenzer, G. D., and B. A. Jones, Jr. 1971. Drop size and impact velocity effects on the detachment of soils by simulated rainfall. Trans. Am. Soc. Agric. Engr. 14(4):625.

Bubenzer, G. D., and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans. Am. Soc. Agric. Engr. 8(1):73.

Chery, D. L., Jr. 1963. Description of a watershed model and rainfall simulator. Ingenusu 3(2):8.

Chow, V. T., and T. E. Harbaugh. 1965. Raindrop production for laboratory watershed experimentation. J. Geophys. Res. 70(24):6111.

Chow, V. T., and B. C. Yen. 1974. A laboratory watershed experimental system. University of Illinois Civil Engr. Stud. Hydr. Engr. Series No. 27.

Cluff, C. B., and D. G. Boyer. 1971. The use of a realistic rainfall simulator to determine relative infiltration rates of contributing watersheds to the Lower Gila below Painted Rock Dam. University of Arizona Water Research Center. p. 113.

Costin, A. B., and D. A. Gilmour. 1970. Portable rainfall simulator and plot unit for use in field studies of infiltration, runoff, and erosion. J. Appl. Ecol. 7(1):193.

Craddock, G. W., and C. K. Pearse. 1938. Surface runoff and erosion on granitic mountain soils of Idaho as influenced by range cover, soil disturbance, slope, and precipitation intensity. U.S. Dept. of Agric. Circ. No. 482. 24 p.

Diebold, C. H. 1951. Soil layers causing runoff from hard land wheat-fields in Colorado and New Mexico. J. Soil Water Conserv. 6:202.

Diseker, E. G., and R. E. Yoder. 1936. Sheet erosion studies on Cecil clay. Alabama Poly. Inst. Agric. Exp. Stn.

Disrud, L. A., and R. K. Krauss. 1971. Examining the process of soil detachment from clods exposed to wind-driven simulated rainfall. Trans. Am. Soc. Agric. Engr. 14(1):90.
Dixon, R. M., and A. E. Peterson. 1964. Construction and operation of a modified spray infiltrometer and a flood infiltrometer. Univ. of Wisconsin Agric. Exp. Stn. Res. Rep. 15. 31 p.
Dixon, R. M., and A. E. Peterson. 1968. A vacuum system for accumulating runoff from infiltrometers. Soil Sci. Soc. Am. Proc. 32(1):123.
Doran, R. L., and R. N. Anderson. 1975. Effects of simulated rainfall on Bentazon activity. Weed Sci. 23(2):105.
Dortignac, Edward J. 1951. Design and operation of Rocky Mountain infiltrometer. Rocky Mt. Forest and Range Exp. Stn. Paper 5. 68 p.
Duley, F. L., and F. G. Ackerman. 1934. Runoff and erosion from plots of different lengths. J. Agric. Res. 48:505.
Duley, F. L., and O. E. Hayes. 1932. The effect of the degree of slope on runoff and soil erosion. J. Agric. Res. 45:349.
Ekern, P. C. 1950. Raindrop impact as the force initiating soil erosion. Unpublished Ph. D. Thesis. University of Wisconsin.
Ekern, P. C., and R. J. Muckenhirn. 1948. Water drop impact as a force in transporting sand. Soil Sci. Soc. Am. Proc. 12:441.
Ellison, W. D. 1947. Soil erosion studies - Part II. Agric. Engr. 28:197.
Ellison, W. D., and W. H. Pomerene. 1944. A rainfall applicator. Agric. Engr. 25(6):220.
Epstein, E., and W. J. Grant. 1966. Design, construction, and calibration of a laboratory rainfall simulator. University of Maine Agric. Exp. Stn. Tech. Bull. 22.
Farmer, E. E., and B. P. Van Haveren. 1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA-Forest Serv. Res. Paper INT-100. 14 p.
Foster, G. R. 1975. Hydraulics of flow in a rill. Unpublished Ph. D. Thesis. Purdue University 222 p.
Gabriels, D., and M. de Boodt. 1975. A rainfall simulator for soil erosion studies in the laboratory. Pedologie 25(2):80.
Gabriels, D., M. de Boodt, and D. Minjauw. 1974. Dune sand stablization with synthetic soil conditions: a laboratory experiment splash erosion. Soil Sci. 118(5):332.
Gifford, G. F., and R. K. Tew. 1969. Evaluating rangeland water quality with small plot infiltrometer. J. Soil Water Conserv. 24(2):65.
Goodman, L. J. 1952. Erosion control in engineering works. Agric. Engr. 33:155.
Grace, R. A., and P. S. Eagleson. 1967. Scale model of urban runoff from storm rainfall. J. Hydr. Div. Am. Soc. Civil Engr. 93(HY3):161.
Grierson, I. T. 1975. The effect of gypsum on the chemical and physical properties of a range of brown earths. Unpublished M.S. Agr. Sci. Thesis. University of Adelaide, South Australia.
Grierson, I. T., and J. M. Oades. 1977. A rainfall simulator for field studies of runoff and soil erosion. J. Agric. Engr. Res. 22:37.
Hall, M. J. 1969. The design of nozzle networks for the simulation of rainfall. J. Hydr. Res. 7:449.
Hall, M. J. 1970. Critique of methods of simulating rainfall. Water Resources Res. 6(4):1104.

Hall, M. J., and P. O. Wolf. 1967. Design criteria for laboratory catchment experiments, with particular reference to rainfall simulation. Int. Assoc. Sci. Hydrol Pub. No. 76:395.

Hamon, W. R. 1979. Infiltrometer using simulated rainfall for infiltration research. In C. R. Amerman (ed.) Infiltration Research Planning Workshop. I. State of Arts Reports. (In press).

Hendrickson, B. H. 1934. The choking of pore space in the soil and its relation to runoff and erosion. Trans. Am. Geophys. Union 14th Ann. Mtg. p. 501.

Hermsmeier, L. F., L. D. Meyer, A. P. Barnett, and R. A. Young. 1963. Construction and operation of a 16-unit rainulator. U.S. Dept. Agric. Pub. ARS 41-62. 136 p.

Holland, M. E. 1969. Design and testing of rainfall system. Colorado State University Exp. Stn. CER 69-70 MEH 21. Fort Collins.

Horton, R. E. 1938. Analysis of simulated rainfall experiments. USDA-SCS TP 18.

Hoyt, L. Arthur. 1968. Rainstorms made to order. Public Works 99(3):95.

Hudson, N. W. Not Dated. The influence of rainfall on the mechanics of soil erosion with particular reference to southern Rhodesia. Unpublished M.S. Thesis. University of Cape Town, South Africa.

Issard, C. F., and M. T. Augustine. 1943. Preliminary report on analysis of runoff resulting from simulated rainfall on paved plot. Trans. Am. Geophys. Union 25:500.

Jager, D. J. 1972. The influences of cultural practices and seeded species on overland flow and sediment production from the Big Stage cover type in East Gate Basin. University of Nevada.

Kelly, L. L. 1940. A comparison of the Colorado and Type F artificial rainfall applicators. SCS Office of Res.

Kiline, M., and E. V. Richardson. 1973. Mechanics of soil erosion from overland flow generated by simulated rainfall. Colorado State University. Hydrol. Paper.

Kinnell, P. I. A. 1974. Splash erosion: Some observations on the splash-cup technique. Soil Sci. Soc. Am. Proc. 38(4):657.

Kisisel, I. T., A. R. Rao, J. W. Delleur, and L. D. Meyer. 1971. Turbulence characteristics of overland flow--the effects of rainfall and boundary roughness. Purdue University School of Engr. Tech. Rep. No. 28.

Klochkov, B. 1972. A rainfall simulator for the study of erosion in laboratories. Pochvozn Agrokhim 7(4):105.

Lane, W. R. 1947. A microburette for producing small liquid drops of known size. J. of Sci. Instru. 24:98.

Langford, K. J. 1970. A review of designs for rainfall simulators. University of Melbourne. Agric. Engr. Rep. 17/70.

Lattanzi, A. R., L. D. Meyer, and M. F. Baumgardner. 1974. Influence of mulch rate and slope steepness on interrill erosion. Soil Sci. Soc. Am. Proc. 38(6):946.

Law, S. M. 1977. Statistical evaluation of rainfall-simulator and erosion testing procedure. Res. Rep. No. 106. State Project No. 736-03-09. Res. Project No. 74-2M(B). Louisiana HPR 1(14). 34 p.

Laws, J. O. Not dated. Drop size and erodibility of the spray from a Grinnel 1.5 nozzle. USDA Mimeograph.

Lowdermilk, W. C. 1930. Influence of forest litter on runoff, percolation and erosion. J. Forestry 28:474.
Lusby, G. C. 1977. Determination of runoff and sediment yield by rainfall simulation. In T. J. Toy (ed.) Erosion: Research techniques, erodibility, and sediment delivery. Geo. Abstracts Ltd., Norwich, England. p. 19.
Lusby, G. C., and T. J. Toy. 1976. An evaluation of surface mined spoils area restoration in Wyoming using rainfall simulation. Earth Surface Processes. p. 375.
Lyles, L., L. A. Disrud, and N. P. Woodruff. 1969. Effect of soil physical properties, rainfall characteristics, and wind velocity on clod disintegration by simulated rainfall. Soil Sci. Soc. Am. Proc. 33(2):302.
Magarvey, R. H., and B. W. Taylor. 1956. Apparatus for the production of large waterdrops. R. Sci. Inst. 27:944.
Malekuti, A., and G. F. Gifford. 1978. Natural vegetation as a source of diffuse salt within the Colorado River basin. Water Res. Bull. 14:195.
Marston, D. 1978. The use of simulated rainfall in assessing the erodibility of various stubble management practices. Proc. Conf. Agric. Engr. p. 74 Toowoomba, Australia.
Mazurak, A. P., L. Chesnin, and A. E. Tiarks. 1975. Detatchment of soil aggregates by simulated rainfall from heavily manured soils of eastern Nebraska. Soil Sci. Soc. Am. Proc. 32(5):716.
Mazurak, A. P., and P. N. Mosher. 1968. Detachment of soil particles in simulated rainfall. Soil Sci. Soc. Am. Proc. 32(5):716.
McCalla, T. M. 1954. Waterdrop method of determining stability of soil structure. Soil Sci. 58:117.
McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 85:185.
McIntyre, D. S. 1958. Soil splash and the formation of surface crusts by raindrop impact. Soil Sci. 85:261.
McKay, M. F., and R. J. Lock. 1978. A modified Meyer rainfall simulator. Proc. Conf. on Agr. Eng. p. 78. Toowoomba, Australia.
McQueen, I. S. 1963. Development of a hand-portable rainfall-simulator infiltrometer. U.S. Geol. Surv. Circ. 482. 16 p.
Mech, Stephen J. 1965. Limitations of simulated rainfall as a research tool. Trans. Am. Soc. Agric. Engr. 8(1):66.
Meeuwig, R. O. 1971. Infiltration and water repellency in granitic soils. USDA-Forest Service Res. Paper INT-111. 20 p.
Meline, H. R. 1968. Rainfall simulation in wind tunnels. Test Engr.
Meyer, L. Donald. 1958. An investigation of methods for simulating rainfall on standard runoff plots and a study of the drop size, velocity, and kinetic energy of selected spray nozzles. USDA-ARS, Spec. Rep. No. 81.
Meyer, L. Donald. 1960. Use of the rainulator for runoff plot research. Soil Sci. Soc. Am. Proc. 24(4):319
Meyer, L. Donald. 1965. Simulation of rainfall for soil erosion research. Trans. Am. Soc. Agric. Engr. 8(1):63.
Meyer, L. D., and W. C. Harmon. 1977. Rainfall simulator for evaluating erosion rates and sediment sizes from row sideslopes. Am. Soc. Agric. Engr. Paper No. 77-2025. Am. Soc. Agric. Engr., St. Joseph, Michigan.

Meyer, L. Donald, and Donald L. McCune. 1958. Rainfall simulator for runoff plots. Agric. Engr. 39(10):644.

Meyer, L. Donald, and E. J. Monke. 1965. Mechanics of soil erosion by rainfall and overland flow. Trans. Am. Soc. Agric. Engr. 8(4):572.

Monke, E. J., H. J. Marelli, L. D. Meyer, J. F. De Jong. 1977. Runoff, erosion and nutrient movement from interrill areas. Trans. Am. Soc. Agric. Engr. 20(1):58.

Moody, F. J., and M. I. Sandsberg. 1944. Devices for producing artificial rainfall for testing water resistant and water proof materials. Philadelphia Quartermaster Depot Proj. 186.

Morin, J., C. B. Cluff, and W. R. Powers. 1970. Realistic rainfall simulation for field investigation. University of Arizona. Water Resource Res. Center. University of Arizona. 22 p.

Morin, J., D. Goldberg, and I. Seginer. 1967. A rainfall simulator with a rotating disk. Trans. Am. Soc. Agric. Engr. 10:74.

Munn, D. A. 1973. Effect of soil, cover, slope, and rainfall factors on soil and phosphorus movement under simulated rainfall conditions. Soil Sci. Soc. Am. Proc. 37(3):428.

Munn, J. R., Jr. Not dated. Part I: Development of the Tahoe Basin rainfall simulator. University of California Water Resources Res. Center, 22 p.

Munn, J. R., and G. L. Huntington. 1976. A portable rainfall simulator for erodibility and infiltration measurements on rugged terrain. Soil Sci. Soc. Am. J. 40(4):622.

Mutchler, Calvin K. 1965. Using the drift of waterdrops during fall for rainfall simulator design. J. Geophys. Res. 70(16):3899.

Mutchler, Calvin K. 1965. Waterdrop formation from capillary tubes. U.S. Dept. Agric. ARS 41-107. 12 p.

Mutchler, Calvin K., and L. F. Hermsmeier. 1965. A review of rainfall simulators. Trans. Am. Soc. Agric. Engr. 8:67.

Mutchler, Calvin K., and W. C. Moldenhauer. 1963. Applicator for laboratory rainfall simulator. Trans. Am. Soc. Agric. Engr. 6:220.

Myers, E. A. 1952. A field plot irrigator. Pennsylvania State College Prog. Rep. No. 83.

Nassif, S. H., and E. M. Wilson. 1975. The influence of slope and rain intensity on runoff and infiltration. Hydrol. Sci. Bull. 20:539.

Neal, J. H. 1938. The effect of the degree of slope and rainfall characteristics on runoff and soil erosion. Missouri University Res. Bull. 280.

Nichols, M. L., and H. D. Sexton. 1932. A method of studying soil erosion. Agric. Engr. 13:101.

Obeid, M., and A. S. E. Din. 1971. Ecological studies of the vegetation of the Sudan. III. The effect of simulated rainfall distribution at different isohyetals on the regeneration of Acacia Senegal (L.) Willd in clay and sandy soils. J. of Applied Ecol. 8(1):203.

Osborn, B. Not dated. Measuring soil splash and protective value of cover on range land. USDA-SCS Mimeographed Report.

Packer, Paul E. 1957. Intermountain infiltrometer. USDA, Forest Service Misc. Pub. No. 14.

Palmer, Robert S. 1962. An apparatus for forming waterdrops. U.S. Dept. Agric. Prod. Res. Rep. 63. 28 p.

Palmer, Robert S. 1962. Water jet breakup. Agric. Engr. 43:456.

Palmer, Robert S. 1963. Water drops for simulating rainfall. New Hampshire Horizons 6(2):7-8.
Palmer, Robert S. 1965. Waterdrop impact forces. Trans. Am. Soc. Agric. Engr. 8(1):69.
Pereira, H. 1956. A rainfall test for structure in tropical soils. J. Soil Sci. 7(1):68.
Peterson, R. J. 1977. Laboratory simulation of soil erosion. Unpublished M.S. Thesis. Colorado State University, Fort Collins. 70 p.
Rasbach, D. J. 1953. The production of water spray of uniform drop size by a battery of hypodermic needles. J. Sci. Instru. 30:
Rauzi, F. 1963. Water intake and plant composition as affected by different grazing on rangelands. J. Soil Water Conserv. 18(3):114.
Rawitz, E., M. Margolin, and D. I. Hillel. 1972. An improved variable-intensity sprinkling infiltrometer. Soil Sci. Soc. Am. Proc. 36(3):533.
Rayner, A. C., and H. Hurtig. 1952. An apparatus for producing uniform drops and its use in insecticide investigation. Suffield Exp. Stn. Tech. Paper No. 22. Ralston, Alberta, Canada.
Rhoades, E. D. 1961. A mobile double-tower sprinkling infiltrometer. J. Soil Water Conserv. 16(4):181.
Riezebos, H. T., and E. Seyhan. 1977. Essential conditions of rainfall simulation for laboratory water erosion experiments. Earth Surface Processes 2:185.
Rogers, W. F. 1970. A portable infiltrometer. University of Nebraska, Omaha.
Romkens, M. J. M., L. F. Glen, D. W. Nelson, and C. B. Roth. 1975. A laboratory rainfall simulator for infiltration and soil detachment studies. Soil Sci. Soc. Am. Proc. 39(1):158.
Rose, C. W. 1960. Soil detachment caused by rainfall. Soil Sci. 89:28.
Rowe, P. B. 1940. The construction, operation and use of the North Fork infiltrometer. California Forest and Range Exp. Stn., Misc. Pub. No. 1.
Schottman, R. W. 1978. Estimation of the penetration of high energy raindrops through a plant canopy. Unpublished Ph. D. Thesis. Cornell University, Ithaca, New York. 132 p.
Seimens, J. C., and W. R. Oschwald. 1978. Corn-soybean tillage systems: erosion control, effects on crop production, costs. Trans. Am. Soc. Agric. Engr. 21(2):293.
Selby, M. J. 1970. Design of a hand-portable rainfall-simulating infiltrometer, with trial results from the Otutira catchment. J. of Hydrol. 9(2):117.
Shachori, A., and I. Seginer. 1962. Sprinkling assembly for simulation of design storms as a means for erosion and runoff studies. Bull. of Int. Assoc. of Sci. Hydrology. 7(4):57.
Sharp, A. L., and H. N. Holton. 1940. A graphical method of analysis of sprinkled plot hydrographs. Trans. Am. Geophys. Union 21:558.
Shriner, D. S., C. H. Abner, and L. K. Mann. 1977. Rainfall simulation for environmental application. Oak Ridge National Lab. Environ. Sci. Div. Pub. No. 1067. 17 p.

Sloneker, L. L. and W. C. Moldenhauer. 1973. Effect of varying the on-off time of rainfall simulation nozzles on surface sealing and intake rates. Soil Sci. Soc. Am. Proc. 38(1):157.

Sloneker, L. L., J. C. Olson, and W. C. Moldenhauer. 1974. Soil-water pressure during intermittent simulated rain application measured with a new rapid response tensiometric technique. Soil Sci. Soc. Am. Proc. 38:985.

Sreenivas, L., J. R. Johnston, and H. O. Hull. 1947. Some relationships of vegetation and soil detachment in the erosion process. Soil Sci. Soc. Am. Proc. 12:471.

Steinhardt, Reuven, and Daniel Hillel. 1966. A portable low-intensity rain simulator for field and laboratory use. Soil Sci. Soc. Am. Proc. 30:666.

Surmach, G. P. 1952. Study of permeability and runoff on detrital chestnut soil by the sprinkling method. Pochvovedenie 10:936.

Swanson, N. P. 1965. Rotating-boom rainfall simulator. Trans. Am. Soc. Agric. Engr. 8(1):71.

Swartzendruber, D., and D. Hillel. 1975. Infiltration and runoff for small field plots under constant intensity rainfall. Water Resources Res. 11(3):445.

Timko, Steve T., C. M. Skau, and M. C. Fleischmann. 1967. A low intensity rain simulator for long duration rain on snow events. Proc. Third Ann. Am. Water Res. Conf., Am. Water Res. Assoc., San Francisco. p. 493.

Turner, A. K., and K. A. Langlord. 1969. A rainfall simulator and associated facilities for hydrologic studies. J. Australian Inst. of Agric. Sci. 35(2):115.

Turner, George T., and Edward J. Dortignac. 1954. Infiltration, erosion, and herbage production of some mountain grasslands in western Colorado. J. Forestry 52:858.

Umback, C. R. 1965. Effects of wind on falling drops. Unpublished M.S. Thesis. South Dakota State University, Brookings.

Umback, C. R., and W. D. Lembke. 1966. Effects of wind on falling waterdrops. Trans. Am. Soc. Agric. Engr. 9(6):805.

van Heerden, W. M. 1964. Splash erosion as affected by the angle of incidence of raindrop impact. Unpublished Ph. D. Thesis. Purdue University, West Lafayette, Indiana. 148 p.

Walker, P. H., T. Hutka, A. J. Moss, and P. I. A. Kinell. 1977. Use of a versatile experimental system for soil erosion studies. Soil Sci. Soc. Am. J. 41(3):610.

Walton, W. H., and W. C. Prewett. 1949. The production of sprays and mists of uniform drop size by means of spinning disk type sprayers. Proc. Phys. Soc. London 62:341.

Weeks, L. E., and W. G. Colter. 1952. Effect of synthetic soil conditioners on erosion control. Soil Sci. 73:473.

White, A. W., Jr., L. E. Asmussen, E. W. Hauser, J. W. Turnbull. 1976. Loss of 2,4-D in runoff from plots receiving simulated rainfall from a small agricultural watershed. J. Environ. Qual. 5(4):487.

Wilm, H. G. 1941. Methods for the measurement of infiltration. Trans. Am. Geophy. Union 22:678

Wilm, H. G. 1943. The application and measurement of artificial rainfall on types FA and F infiltrometers. Trans. Am. Geophys. Union 24:480.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979—691—928/273

Woodburn, R. 1948. The effect of structural condition on soil detachment by raindrop action. Agric. Engr. 29:154.
Woodruff, C. M. 1948. Erosion in relation to rainfall, crop cover and slope on a greehouse plot. Soil Sci. Soc. Am. Proc. 12:475.
Woodruff, C. M., D. D. Smith, and D. M. Whitt. 1938. Results of studies involving the application of rainfall at uniform rates to control plot conditions. USDA-SCS Mimeographed Rep.
Woodward, L. 1943. Infiltration capacities of some plant soil complexes on Utah range watershed lands. Trans. Am. Geophys. Union 24:468.
Yates, W. E. Not dated. An analysis of automization by rotating disk for controlled droplet size. Unpublished M.S. Thesis, University of California.
Yerkhov, N. S. 1975. Method for determining pressureless soil permeability during sprinkling. Soviet Soil Sci. 7(5):624.
Young, R. A., and R. E. Burwell. 1972. Prediction of runoff from natural rainfall using a rainfall simulator. Soil Sci. Soc. Am. Proc. 36(5):827.
Zingg, A. W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Engr. 21(2):59.

U. S. DEPARTMENT OF AGRICULTURE
SCIENCE and EDUCATION ADMINISTRATION
WESTERN REGION
1333 BROADWAY, SUITE 400
OAKLAND, CALIFORNIA 94612

Return the mailing label(s) to above address if:

- ☐ Your name or address is wrong (indicate corrections, including ZIP).
- ☐ You receive duplicate copies (include labels from all copies received).
- ☐ You do NOT wish to continue receiving this technical series.